RTD-TDR-63-4262

DECONTAMINATION OF HYDRAULIC FLUIDS

TECHNICAL DOCUMENTARY REPORT No. RTD-TDR-63-4262

[redacted]

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DIRECTORATE OF AGE ENGINEERING
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 912A, Task No. 97092

Prepared under Contract No. AF 33(657)-9958
by Oklahoma State University, Stillwater, Oklahoma
Authors: Personnel of the Fluid Power Controls Laboratory

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NOTICES

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FOREWORD

This Technical Document Report was prepared by the Fluid Power Controls Laboratory of the School of Mechanical Engineering, Oklahoma State University of Agriculture and Applied Science. The work was initiated by the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, and accomplished under contract AF 33(657)-9958.

This contract with Oklahoma State University was initiated under ASD Maintenance and Test Branch and is titled "Decontamination of Hydraulic Fluids." It is being accomplished under the technical monitorship of Mr. Theodore C. Ning, SEG (SEHBM), Air Force Project Engineer, and under the general technical guidance of Herbert E. Spencer, Chief, Maintenance and Handling Equipment Branch. The work on the project was divided into separate parts, whereby the responsibility for each part was assigned to a different member of the hydroclone team working under the direction of Dr. E. C. Fitch, Project Leader; R. E. Reed, Assistant Project Leader; and R. E. Bose and C. R. Gerlach, Technical Project Leaders. The individual work assignments were as follows:

Separation Efficiency Tests -- W. R. Lynn, Graduate Assistant
Pressure Drop Tests -- J. W. Webb, Graduate Assistant
Collection Chamber Study -- M. L. Rogers, Graduate Assistant
Instrumentation -- C. Y. Ma, Graduate Assistant
Non-Lubricating Fluid Tests -- J. A. Jones, Graduate Assistant
Materials Evaluation -- W. T. Wittmer, Graduate Assistant

The primary objective of the Hydroclones for Decontamination of Hydraulic Fluids Program is the design, development, and application of miniature hydroclone prototypes for decontaminating hydraulic fluid in Air Force Ground Support equipment. This program encompasses the following technical areas: Separation efficiency tests, pressure drop tests, collection chamber study, facilities implementation, non-lubricating fluid tests, and materials evaluation.

This report covers work conducted from 27 December 1962 to 27 December 1963 under contract AF 33(657)-9958.

ABSTRACT

This report includes a description of the design, development, and application of miniature hydroclone prototypes for decontaminating hydraulic fluid in Ground Support equipment. The hydroclone is defined, described and explained in a manner appropriate for an introductory treatise. The specialized equipment acquired or constructed for implementation of the Hydroclone Project is delineated, as are its applications to the hydroclone study. The comprehensive investigation to determine the parameters for an optimum hydroclone for MIL-F-5606 hydraulic fluid is related, and the final values of these parameters which comprise the prototype hydroclone for MIL-F-5606 are given. A unique method for endurance testing of materials for hydroclone fabrication is portrayed, and the findings of these tests are reported herein.

PUBLICATION REVIEW

This report has been reviewed and is approved:

W. A. Rose
Chief, Airfield & Hangar Equipment Division
Directorate of AGE Engineering
Deputy of Systems Engineering

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ILLUSTRATIONS

SYMBOLS

A	Dimensionless flow parameters
A_1	Inlet Area, sq. in.
B	Angle of inlet nozzles, degrees
B_e	Effective dimensionless inlet radius
B_r	Dimensionless inlet radius, r_1/r_c
C, C_1, C_2, C_3, C_4, C_8	Constants
C_{Di}	Coefficient discharge, inlet
C_{Do}	Coefficient of discharge, overflow
D	Particle diameter, microns
D_1, D_2, D_3, D_4,	Downstream average of particle count, microns
D_c	Diameter of cone, inches
D_i	Diameter of inlet, inches
D_o	Diameter of overflow, inches
D_u	Diameter of underflow, inches
D_{cc}	Diameter of collection chamber, inches
$D_{50\%}$	Diameter (microns) of particles experiencing 50% separation
E_r	Range efficiency, %
F_c	Centrifugal force, lbs
F_D	Viscous drag force, lbs
G	Dimensionless radial position, R/r_c
g_c	Gravitational conversion factor, in/sec^2
K	Constant
K_1	Conversion factor, 1.275×10^4
L_1	Length of cyclone cylindrical section, inches
L_2	Length of vortex finder, inches
L_{cc}	Length of collection chamber, inches
L_{sc}	Length of subcone, inches
N	Number of inlet nozzles
N_i	Inlet efficiency, %
N_p	Placement about circumference
n	Empirical value
P_c	Pressure drop across the cone section, psi
P_i	Pressure drop across the inlet, psi

P_T	Total pressure drop across the hydroclone, psi
Q	Flow rate, gpm
R	Radial position in hydroclone, inches
r_c	Radius of hydroclone, inches
r_i	Radius of inlet, inches
r_o	Radius of overflow, inches
r_p	Radius out to pressure probe on the overflow, inches
U_1, U_2, U_3, U_4,	Upstream average of particle count, microns
V	Dimensionless tangential velocity, V_t/v_c
V_o	Dimensionless tangential velocity, v_o/v_c
V_R	Radial velocity of fluid, in/sec
V_t	Tangential velocity, inches/sec
v_c	Tangential velocity at $R = r_c$, inches/sec
v_i	Inlet tangential velocity, inches/sec
v_o	Tangential velocity at $R = r_o$, inches/sec
γ	Angle of subcone, degrees
δ	Dimensionless overflow radius, r_o/r_c
δp	Dimensionless overflow pressure probe radius, r_p/r_c
Δp	Pressure difference across an annular layer of rotating fluid, psi
ΔR	Thickness of annular layer, inches
μ	Viscosity of fluid, lb sec/in^2
ρ_L	Density of liquid, lb sec^2/in^4
ρ_s	Density of particles, lb sec^2/in^4
φ	Hydroclone cone angle, degrees
ω	Angular velocity, radians/sec

Q	Flow rate, gpm
R	Radial position in hydroclone, inches
r_c	Radius of hydroclone, inches
r_i	Radius of inlet, inches
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δ	Dimensionless overflow radius, r_o/r_c
δp	Dimensionless overflow pressure probe radius, r_p/r_c
Δp	Pressure difference across an annular layer of rotating fluid, psi
ΔR	Thickness of annular layer, inches
μ	Viscosity of fluid, lb sec/in^2
ρL	Density of liquid, lb/sec in^4
ρ_s	Density of particles, lb/sec^2
φ	Hydroclone cone angle, degrees
ω	Angular velocity, radians/sec

SECTION 1

INTRODUCTION

In the continuing search toward perfection conforming to the nature of neoteric applied science, it is often necessary to revert to the study of basic elements in order to solve the most complex problems. Precision-designed components have become an outstanding engineering characteristic of our times. And this growth of scientific endeavor has simultaneously multipled the inherent problems to be expected in a high-level technology.

Such a problem as particulate contamination takes on critical aspects when it appears in the hydraulic systems of vital machinery. Through the co-operative efforts of the Hydroclone Research Laboratory of Oklahoma State University and Wright-Patterson Air Force Base an effective solution to contamination control in hydraulic fluids used in ground support equipment has been derived.

This report is a summary of the work concerned with the establishment of design criteria required for fabricating miniature hydroclones to satisfy Air Force requirements for decontaminating hydraulic fluids used in ground support equipment. Also, the actual fabrication of optimum hydroclones designed by the established criteria is discussed.

In order to accomplish the objectives of the program, as they are outlined in the Statement of Work of the referenced contract, testing facilities have been designed and fabricated, or obtained otherwise, to enable a comprehensive study of hydroclone characteristics to support design criteria. Special hydraulic systems that are specifically suitable for controlling the conditions under which experimental hydroclones operate have been erected. Instrumentation setups have been assembled to measure the system variables as the hydroclone and fluid parameters are varied. Equipment for injecting a controlled amount of contaminant (AC Fine Test Dust) into the test system's fluid stream, along with automatic particle counters to measure contamination levels, have been integrated with the hydroclone testing system. Experimental model hydroclones which facilitate the incremental variation of a hydroclone's physical parameters have also been designed and fabricated in support of the hydroclone study. To summarize, it can be said that the Hydroclone Testing Laboratory at Oklahoma State University now contains a fine assemblage of power equipment and instruments to conduct studies in support of hydroclone design and evaluation.

Hydroclone research under the referenced contract has been conducted in three main phases of study: a pressure drop study, a separation efficiency study, and a hydroclone materials study. The pressure

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drop study has been analytical in nature, with experimental support, while the separation efficiency and the materials study have been mainly experimental.

The optimum hydroclone, as discussed in this report and other reports submitted under contract AF 33(657)-9958, is defined as the unit that develops the maximum separation efficiency with the lowest pressure drop across the unit. Mainly, the experimental investigations in this study have been conducted using MIL-F-5606 hydraulic fluid and AC Fine Test Dust. The prototype hydroclones that are to be submitted to the Air Force are devices that were optimized using MIL-F-5606 hydraulic fluid as the specified test media and AC Fine Test Dust as the contaminant. However, the general design criteria is established for other hydraulic fluids and contaminants; and the design procedure, as presented in this report, is applicable for hydroclones operated at flow rates not exceeding 30 gpm.

SECTION II

FUNDAMENTAL CONCEPTS OF HYDROCLONES

A. INTRODUCTION

Machines which are powered and controlled by fluid systems have become one of the true symbols of modern technology. Since particulate contamination in fluid systems can destroy their reliability and effectiveness, a means must be provided for achieving and maintaining clean fluid. Conventional barrier type filters have been applied to control contamination levels in fluid systems; however, such devices periodically become plugged and bypass particle-laden fluid to the unprotected system. The quest for a non-bypass filter having an almost unlimited capacity for contaminants has led to the consideration of many novel devices. This report is concerned with a particulate separator capable of providing clean fluid and meeting the requirements desired for sophisticated systems.

The device being considered is termed a hydroclone and cannot be referred to as a filter according to the definition of the word. A hydroclone is a vortical separator whose dispersion medium is a liquid. Its basic principle of operation is equivalent to that of industrially applied cyclones which utilize relatively high accelerations to achieve desirable partial separation of heterogeneous mixtures. Cyclones have been successfully applied to a multitude of different industrial processes. As a separating unit, the capabilities of cyclones extend to fluid mixtures. Fluid mixtures may consist of two or more immiscible liquids combined in an unstable emulsion, or the mixture may consist of liquid and gaseous components. Separation of solids from fluids by cyclones has been accomplished where the fluid has been either a gas or a liquid.

A cyclone unit of classical configuration is shown in Fig. 1. It consists of a cylindrical section (A) mounted on a truncated cone (B) with an inlet nozzle (C) that directs flow into the inner cylindrical section tangentially. The opening at the apex of the truncated cone serves as the underflow nozzle (D) and a tube extended partially into the center of the cylindrical section serves as an overflow nozzle (E). This tube is generally referred to as the "vortex finder." The underflow pot (F), shown at the apex of the cone section, is a collection chamber for particles that are separated in the cone and discharged through the underflow. Particular cyclone units may or may not use an underflow pot, this being the distinction between closed and open underflow units.

Fig. 2 illustrates the general concepts of the composite flow patterns and the resulting particle separation encountered in a cyclone unit. Sub-section II-D goes into the theoretical aspects of the flow patterns and particle trajectories.

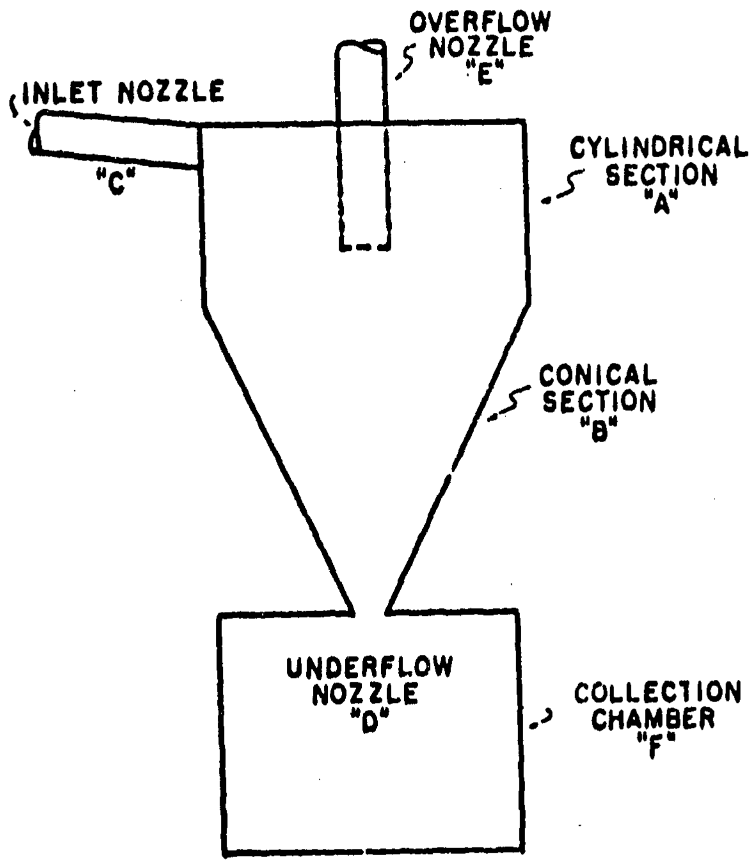

Fig. 1. Classical Hydroclone Configuration.

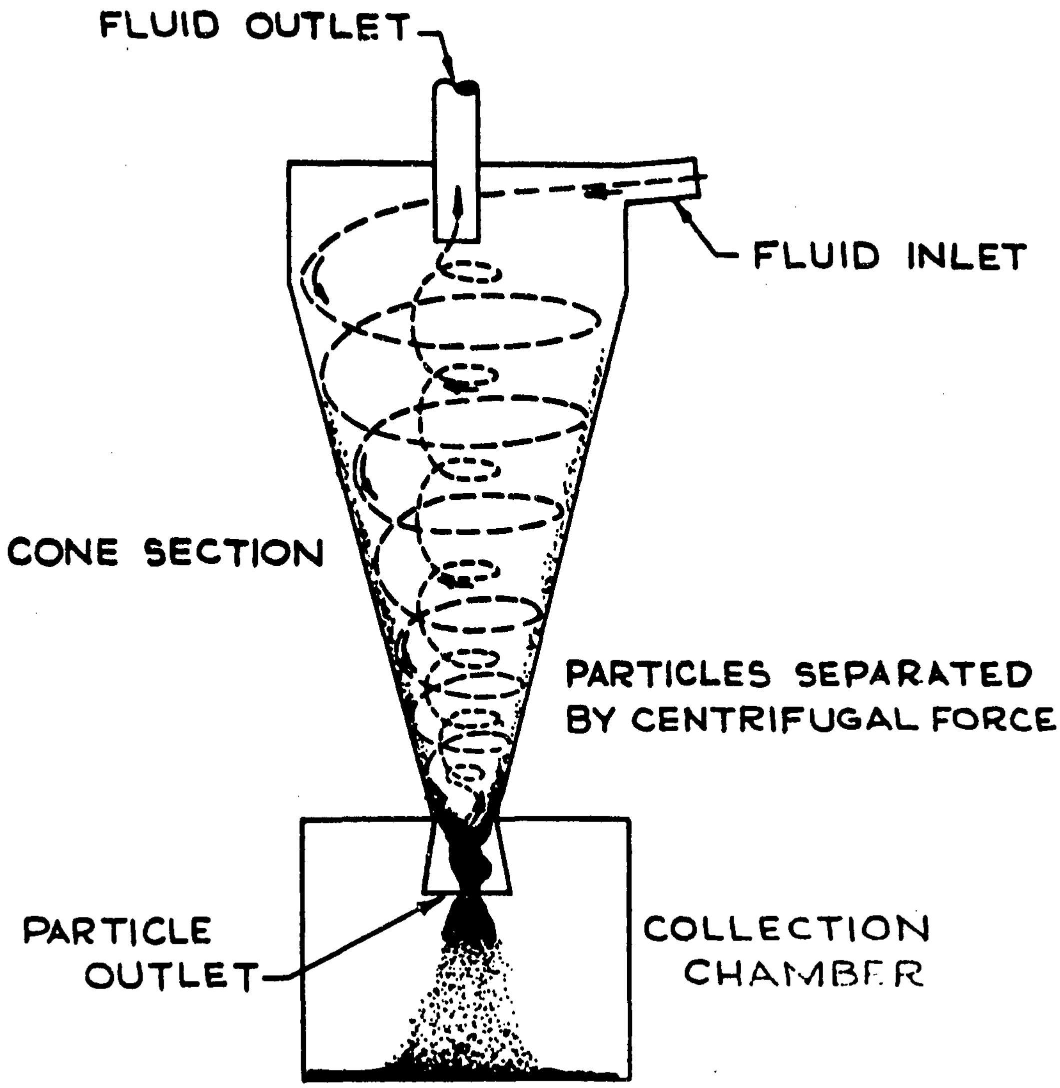

Fig. 2. General Concepts of a Hydroclone Operation.

To provide additional background information regarding cyclone phenomena, and the terminology associated with cyclones, Sub-section II-B presents a review of the history of cyclone applications and developments prior to OSU hydroclone studies. Interestingly, historical literature on cyclones supports the opinion that cyclone applications may have preceded most of its early developments.

Sub-section II-C reviews the hydroclone studies of Oklahoma State University, and Sub-section II-E exhibits typical curves characteristic of hydroclone units.

B. HISTORICAL DEVELOPMENT AND APPLICATION

The first applications employing the cyclone principles date back to 1885 when the dust cyclone came into use. During the early part of the 1900's, dust collector cyclones became more or less common in industry. Based on available literature, the only uses of the cyclone during this period were as dust collectors or fly-ash collectors, operating in conjunction with coal and wood-fired furnaces. The Knickerbocker Company of Jackson, Mississippi, and the Allington and Curtis Manufacturing Company of Saginaw, Michigan owned two of the earliest patents on the dust cyclone. Interestingly, although many changes have been introduced during their development stages, the present day hydroclones closely resemble the old dust collectors. The removal of dust from gases is still one of the most prevalent applications of process cyclones. For example, cyclones are very applicable for removing pollutants from air. Because of the volume of gas to be treated, dust collector installations are appreciably larger than the solid-liquid hydroclones. Probably the most comprehensive contribution to the design details for gas cyclones was published by A. J. ter Linden (59)* in 1949.

Although a specific application of a hydroclone in 1914 is mentioned in the literature, seemingly very little development of the hydroclone materialized prior to the 1930's. Judging from the lack of cyclone articles, other than those pertinent to dust collectors, any development of hydroclones before the 1930's must have been highly specialized and regarded as trade secrets. At least, developments were not publicized.

Gas-liquid cyclones perform very much like the dust cyclones (74). For effective gas-liquid separation in a cyclone, the liquid should not be too finely dispersed in the gas. In general, the liquid-droplet gas ratio should be as uniform as possible. The most common use of the gas-liquid cyclones today is power-plant steam cleaning. In 1942, Pollak and Work (70) presented a complete review of gas-liquid cyclones.

Liquid-liquid cyclones have proven to be relevant to various processes of the chemical industry (71). In chemical engineering applications, the cyclone has served as a chemical mixer-settler in systems where the cyclone excites rapid liquid phase reactions, followed by produce separations. As immiscible fluid separators, their purpose may be to obtain one of the constituents in as pure a form as possible, or in

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*Numbers in parenthesis indicate items in the Bibliography.

other cases it might be desirable to divide the mixture into two fractions, each containing a minimum of the other. Multistage cyclone systems, several units placed in series, have been used to effectuate greater separation in liquid-liquid cyclone applications. But on the other hand, a cyclone, engaged in a liquid-liquid process where comminution of the droplets occurs, will act as a homogenizer rather than a separator (74). This phenomenon is due to complicated rheological properties of the emulsion, high viscosities, and the shearing stresses that exist in cyclones.

Almost fifty years passed from the time that the dust collector cyclone made its debut until the cyclone was applied to wet slurries. In 1939, M. G. Driessen (36) of the Dutch State Mines Laboratory published an article introducing the cyclone as a thickener to increase the densities of suspensions produced during coal cleaning by the "sink-float" process. Originally, the article was printed in French, and hence it received little attention in the United States. A notable difference in Driessen's hydroclone and those of today is the lack of a vortex finder in his configuration. The Dutch State Mines Laboratory continued its development of the hydroclone and introduced the first hydroclone to become well known in the U. S. Publication in regard to the Dutch State Mines' hydroclone was made in 1945. By then, the D.S.M. hydroclone included a vortex finder in its design. Actually, it was not until 1949 that the hydroclone became widely accepted in the U. S. -- ten years after its formal introduction by Driessen.

In the cyclones role as a hydroclone, its flexibility has been most pronounced. For example, some of the specific applications of hydroclones are termed: grading, thickening, purifying, and filtration. The term "grading" is usually used when referring to hydroclones which separate solid particles into two factions. In a grading process, a liquid is used as an auxiliary medium. Hydroclones have proved to be particularly applicable to grading because of the high shearing stresses that exist in their operation. These stresses cause suspension of the particles within the hydroclone and oppose flocculation.

In general, hydraulic-thickener cyclones are units operating with an open underflow. The main objective of this type of process is to execute a division of a solid-liquid mixture into two factions, one containing most of the liquid and a minimum of the solid material, and the other containing most of the solid material together with a small amount of liquid. Thickener type hydroclones have been employed quite successfully in a variety of industrial applications. They are particularly applicable to processes involving large quantities of a suspension.

Employing the hydroclone as a filtering unit is a more recent innovation of cyclone application. The object of the filtering processes is to produce a clean filtrate. In principle, the filtering applications of a hydroclone are very similar to thickener applications; however, cyclones with closed underflow are generally used in the filtering process. The main difference between the two operations is in the end product, and usually the requirements on the degree of separation of the solid and liquid components is much greater for filtering. As might

be expected, increases in separation requirements are accompanied by an increase in the critical nature of the design parameters of the hydroclone, but not necessarily in direct proportion. It should be noted that at this time, there is no known mechanical means that accomplishes complete separation of solid particles from a liquid.

C. HYDROCLONE STUDIES AT OSU

Cyclone study was instituted at Oklahoma State University in 1955, under a fellowship grant by the Pan American Petroleum Corporation. Richard L. Lowery (60) now on the OSU Mechanical Engineering staff, conducted research to determine the feasibility of utilizing the cyclone principle to effect liquid-liquid separation of two immiscible liquids. The reality that hydroclone development was still in its infancy in 1955 is verified by the fact that no publications relevant to liquid-liquid separation by cyclones could be found at that time. For qualitative direction in his laboratory analysis, Mr. Lowery made an interesting analogy between the fluid globule of the dispersion phase and the solid particle of a solid-liquid system. Within the limits of practicability, the analogy was applied with reference to work that had been done in solid-liquid cyclone systems by H. E. Criner (31). Lowery concluded that the cyclone could be used to separate two immiscible liquids on unstable emulsion provided the liquids had properties characterized by those in his investigations.

It is pertinent to note that as a result of Lowery's initiating cyclone study at OSU, definite academic interest was generated in the Mechanical Engineering Department relating to the separation of solids from a hydraulic fluid.

The need for an adequate analytical method for evaluating the ability of a small hydroclone to separate solid particles from hydraulic fluid prompted a master's degree candidate, J. S. Gilbert (49) to hydroclone research at OSU in 1959-60. At the time of his research, Gilbert was a Graduate Research Assistant working as one member of a team of OSU personnel on the "Fluid Contamination Project" sponsored by Oklahoma City Air Materiel Area, Tinker Air Force Base, Oklahoma. The project work in "An Experimental Evaluation of a Hydroclone" is reported in Fluid Contamination Project, Report No. 3, Contract No. AF 34(601)-5470, Project Authorization Nr 5, AMC (Pub)-R60. Gilbert's objective was to develop and verify experimentally an analytical expression for particle separation by the hydroclone. His development consisted of making a force balance on a hypothetical particle within a hydroclone while applying Driessen's equation for tangential velocities in a cyclone. To simplify its practical application, Gilbert applied electronic analog techniques to solve his analytical expression. Mr. Gilbert concluded, after experimental verification involving the separation of glass beads from hydraulic fluid, that his equation was sufficiently accurate to predict the ability of a "small" hydroclone to eliminate solid contaminants from hydraulic fluid. At least, more insight to the problem of separating solid particles from liquids via the hydroclone was afforded by Gilbert's study which interested people at OSU, and future study was planned for the contamination project.

Another analytical expression for particle separation in a hydroclone was included in an M. S. Thesis at OSU in 1961 by J. F. Beattie (10). In the development of his expression, Beattie included an additional reactive force in a force balance on a hypothetical particle in motion in a hydroclone. The additional force considered being the requirement necessary to accelerate the mass of fluid particles set into motion by the relative motion of the solid particles through the fluid medium. Electronic analog techniques were again employed in the solution of Beattie's expression, and the results were found to be in agreement with available experimental data. Mr. Beattie's work was not connected with the Contamination Project of OCAMA's at OSU.

Based on the results obtained from the hydroclone study reported in the Fluid Contamination Project, Report No. 3, a new contract (AF 34(601)-5170, Project Authorization Nr 7, OSU Project Leader: E. C. Fitch) was initiated between Oklahoma State University and Oklahoma City Air Materiel Area on 12 October 1960. The specific emphasis of the negotiated contract was directed toward studying the effects of environmental conditions and various flow parameters on hydroclone behavior. However, in January 1961, OSU agreed to a modification of emphasis in said contract due to a request by OCAMA suggesting that project research would be of more immediate value to OCAMA in their satisfying the objectives of an AMC Directive concerned with the regeneration and evaluation of wire cloth filter elements. Between 12 October 1960, and January 1961, only two work phases pertinent to hydroclone study were initiated:

(a) The design and fabrication of a 40-horsepower hydroclone test stand which would be suitable for testing hydroclones when installed in an environmental chamber.

(b) An analog study of design parameters affecting the behavior of the classical hydroclone.

The results of these two phases were transmitted to OCAMA in Fluid Contamination Project Report No. 4, September 1961.

After OCAMA dropped the sponsorship of the hydroclone studies at OSU to permit the pursuit of filter cleaning information, the Division of Engineering Research at OSU provided the sponsorship for the work. During the period 1 February 1961 to 1 September 1962 under OSU sponsorship, a comprehensive understanding of vortical flow was gained by project personnel. New concepts of hydroclone design were pursued which culminated in a patent application. One hydroclone configuration containing optimum parametric values was demonstrated at Castle Air Force Base in August 1961. This unit successfully maintained the hydraulic fluid in a ground support cart to the desired 3 mg/liter contamination level required by the Air Force.

In January 1962, OCAMA requested OSU to provide them a prototype hydroclone which was comparable in design to the hydroclone that had been demonstrated by OSU at Castle Air Force Base. The request came under Amendment No. 2 to Order No. 62-2 Fluid Contamination Project,

Contract AF 34(601)-9879. The unit was to be used for cleanup of the F-105 Sundstrand, Constant Speed Drive Systems. OSU was to participate in a calibration test run and a test cell run at Tinker Air Force Base prior to depot and extended field tests at a base selected by OCAMA.

During the period from October 1960 to 1 January 1961, Charles R. Gerlach and Robert E. Bose, who are presently associated with the WPAFB Hydroclone Research Project as Technical Team Leaders, became closely associated with hydroclone study as it was emphasized in the Fluid Contamination Project's activities. They both elected to write their respective M. S. thesis using the hydroclone as subject matter. During the period September 1961 to July 1962, Mr. Gerlach became active in hydroclone research mainly through academic interest since he was the recipient of a National Science Foundation Fellowship Grant. Mr. Bose's engagement in hydroclone research came through an OSU departmental assignment under the extension of a Research Assistantship Grant by the University. After the forementioned change of project emphasis, Gerlach's and Bose's hydroclone studies came under departmental sponsorship in order that they could complete their academic endeavors toward the M.S. degree.

Bose submitted an M. S. Thesis (16) on his development of an expression to predict the movement of solid particles in a hydroclone. His development showed a more complete inclusion of actual hydroclone flow phenomena than that of previous work done at OSU. Electronic analog technique was applied to solve his expression and several hydroclones were built which experimentally verified the analytical results obtained in the solution.

Gerlach submitted his M. S. Thesis (48) on the development of a set of equations for separation efficiency and pressure drop from which hydroclones could be designed. His specific intentions were to develop the design equations in terms of the hydroclone parameters.

The work of Gerlach and Bose with hydroclones at OSU has been outstanding in that they have been able to design hydroclones for separating low-micron particles from viscous fluids. Their success marks the validity of their analytical developments, and it has led directly to the hydroclone optimization research that is in progress at OSU.

D. BASIC DYNAMICS OF CYCLONIC FLOW

Hydroclones are employed in two-phase systems involving solid particles entrained in a liquid. The liquid in cyclonic flow traverses complex three dimensional flow paths, and therefore, exhibits velocity vectors which can be described as: tangential, radial, and axial. The solid particles co-existing with the liquid are subjected to three forces created by the relative movement of the liquid and the particles as follows:

(a) Centrifugal force -- an inertia force related to the tangential velocity of the particle.

(b) Centripetal force -- caused by the radially moving fluid dragging the particle.

(c) Axial force -- caused by the axially moving fluid dragging the particle.

The vector sum of the three forces at a given time determines the velocity vector of the particle. The three dimensional velocity patterns for the particles prescribe the trajectory of a given particle. In order to visualize the phenomena of two phase cyclonic flow, the velocity characteristics of the liquid must be studied separately from those displayed by the particles.

1. Fluid Behavior

The fluid entering a hydroclone is accelerated by the pressure differential existing across the inlet orifice. The ingressing fluid is introduced in a slightly downward direction and tangentially to the walls of the cone. The characteristics of the entering fluid and the geometry of the hydroclone creates a strong vortical field. A vortical field possesses pressure gradients that accelerate the fluid in both radial and axial directions. In addition, the swirling fluid, characteristic of a vortical field, passes from a free vortex state to a forced vortex condition.

A free vortex is characterized by irrotational flow in which individual fluid particles do not rotate about their own axis. The tangential velocity associated with a free vortex is described by the relation

$$V_t = \frac{C}{R} \qquad \text{Eq. 1}$$

in which C = Constant, and R = Radius.

A forced vortex condition results from the application of a torque and produces solid body rotation. The forced vortex displays rotational flow in which each individual fluid particle rotates about its own axis. The tangential velocity for fluid in a forced vortex is given by the equation

$$V_t = \omega R \qquad \text{Eq. 2}$$

in which ω = angular speed of the forced vortex, and R = radius.

The tangential velocity of fluid in vortical flow increases with decreasing radius across a free vortex as indicated by Eq. 1 and decreases with decreasing radius in a forced vortex in accordance with Eq. 2. The transition zone between the free and forced vortéces occurs

at the point of maximum tangential velocity of the free vortex and is the shearing section of the vortical field supplying the torque to the forced vortex. The graph shown in Fig. 3 illustrates the physical significance of Eqs. 1 and 2. The relative pattern of the tangential velocities existing in a hydroclone are evidenced from the typical curves shown in Fig. 4.

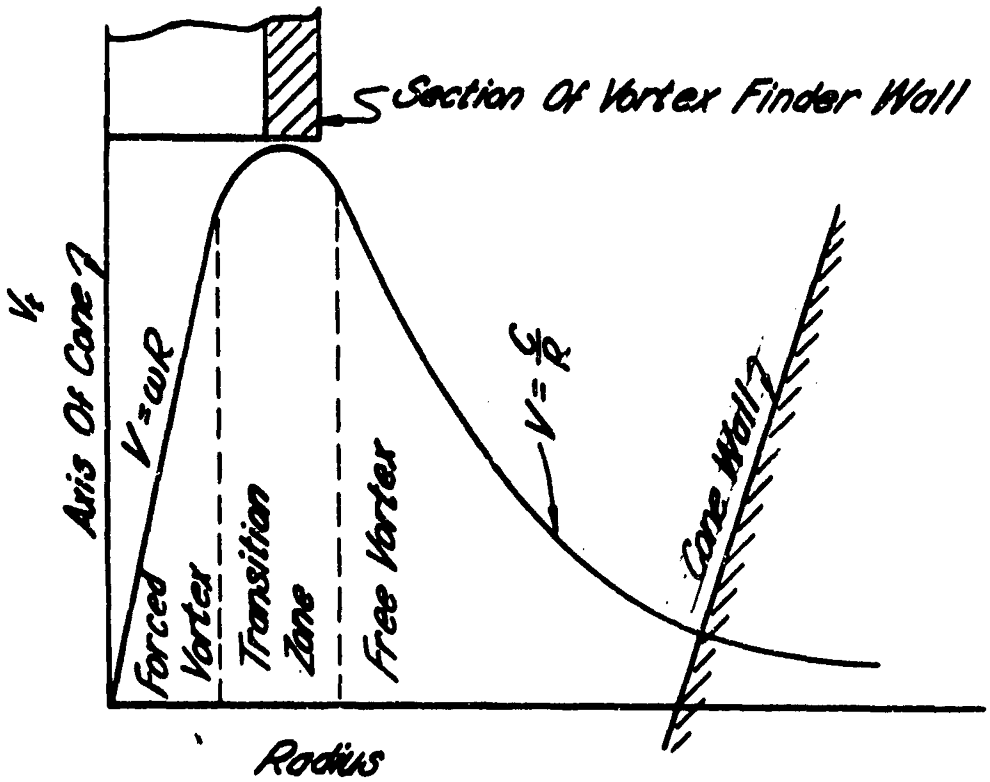

Fig. 3. The Vortical Field.

The fluid entering a hydroclone is focused in a slightly downward direction; and the downward velocity of the fluid, adjacent to the cone wall, continues to increase due to the geometry of the cone. Although the downward velocity of the fluid is significant at the apex of the cone, the quantity of fluid represented becomes negligible. The fluid moving toward the center of the cone experiences a transition from a downward velocity to an upward velocity. The magnitude of the upward velocity within the forced vortex is many times greater than the cone wall vertical velocities. Typical curves for vertical velocities existing in a vortical field are as shown in Fig. 5.

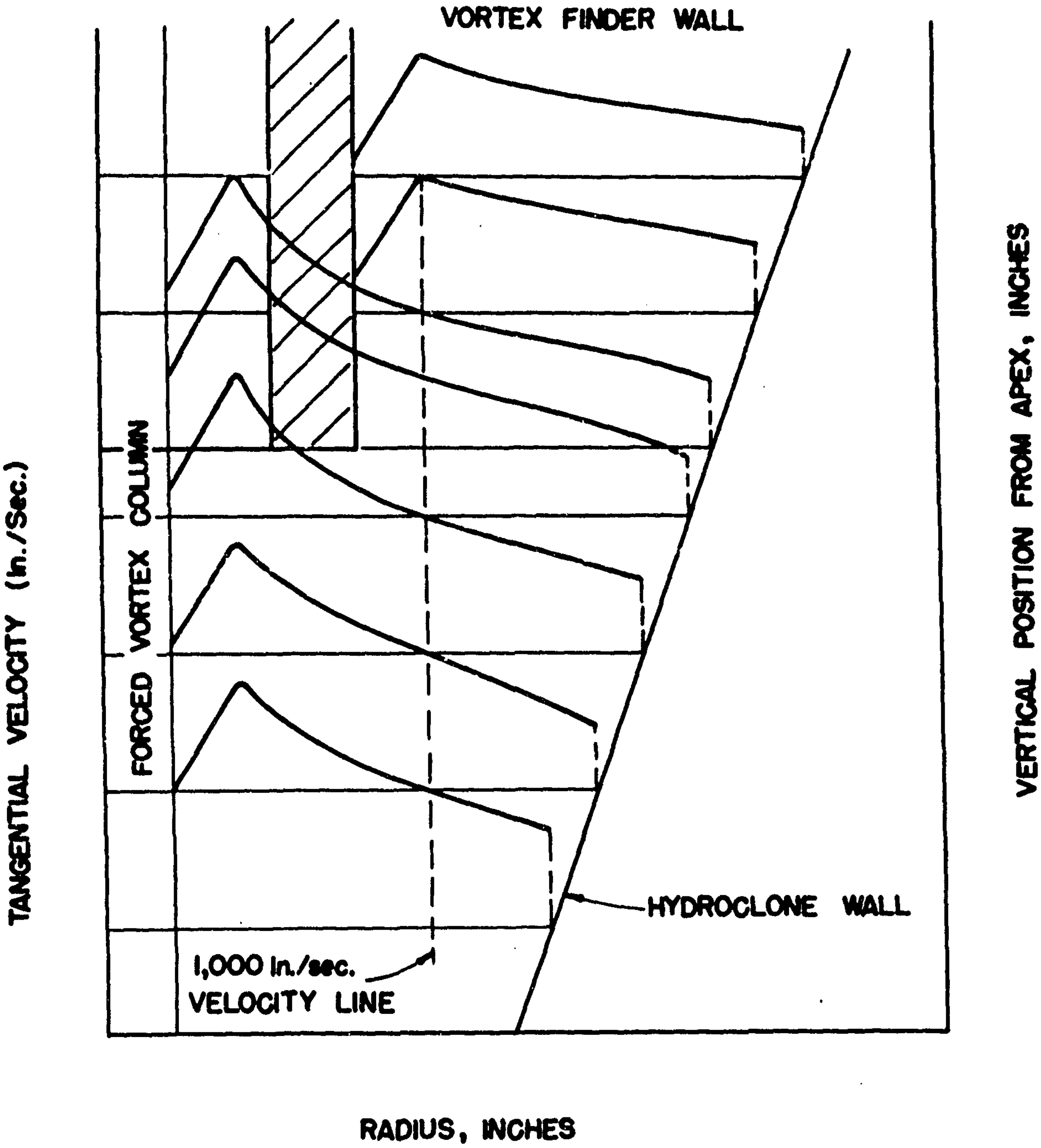

Fig. 4. Tangential Velocity Versus Radius in a Hydroclone. (The curves are referenced to their respective zero datum by dash lines.)

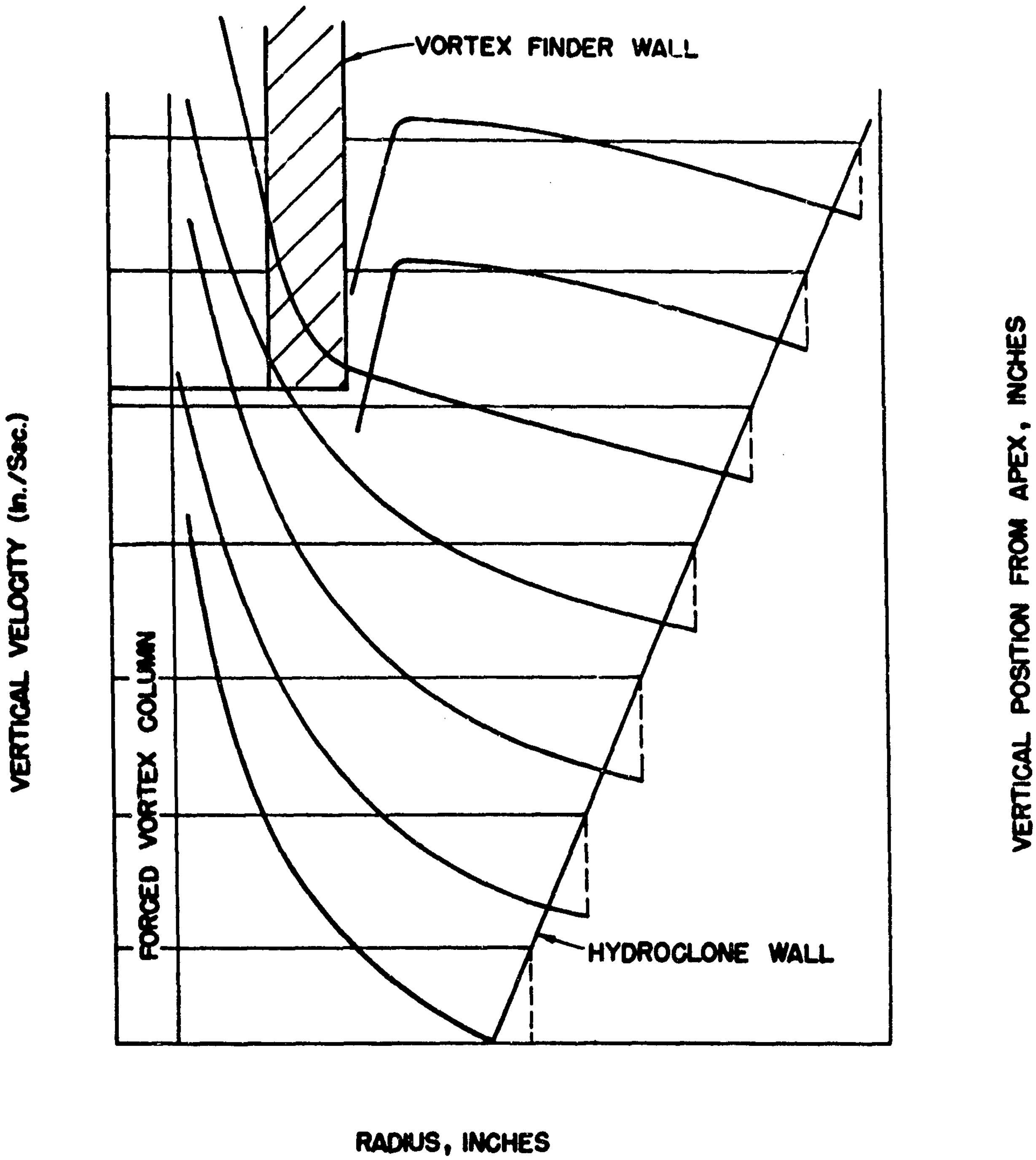

Fig. 5. Vertical Velocities Versus Radius in a Hydroclone. (The curves are referenced to their respective zero datum by dash lines.)

The radial velocity of the fluid in a vortical field continues to increase toward the apex of the cone. At a given horizontal position, the radial velocity is greatest at the cone wall and approaches zero somewhwere between the cone wall and the axis of the cone. In the vicinity of the vortex finder, the radial velocity is reversed in sign and a circulation pattern or eddy current appears. The high radial velocities at the cone wall are attributed to the vertical velocity being deflected by the cone wall and added to the radial velocity component. A typical illustration representing radial velocity patterns in a vortical field is shown in Fig. 6.

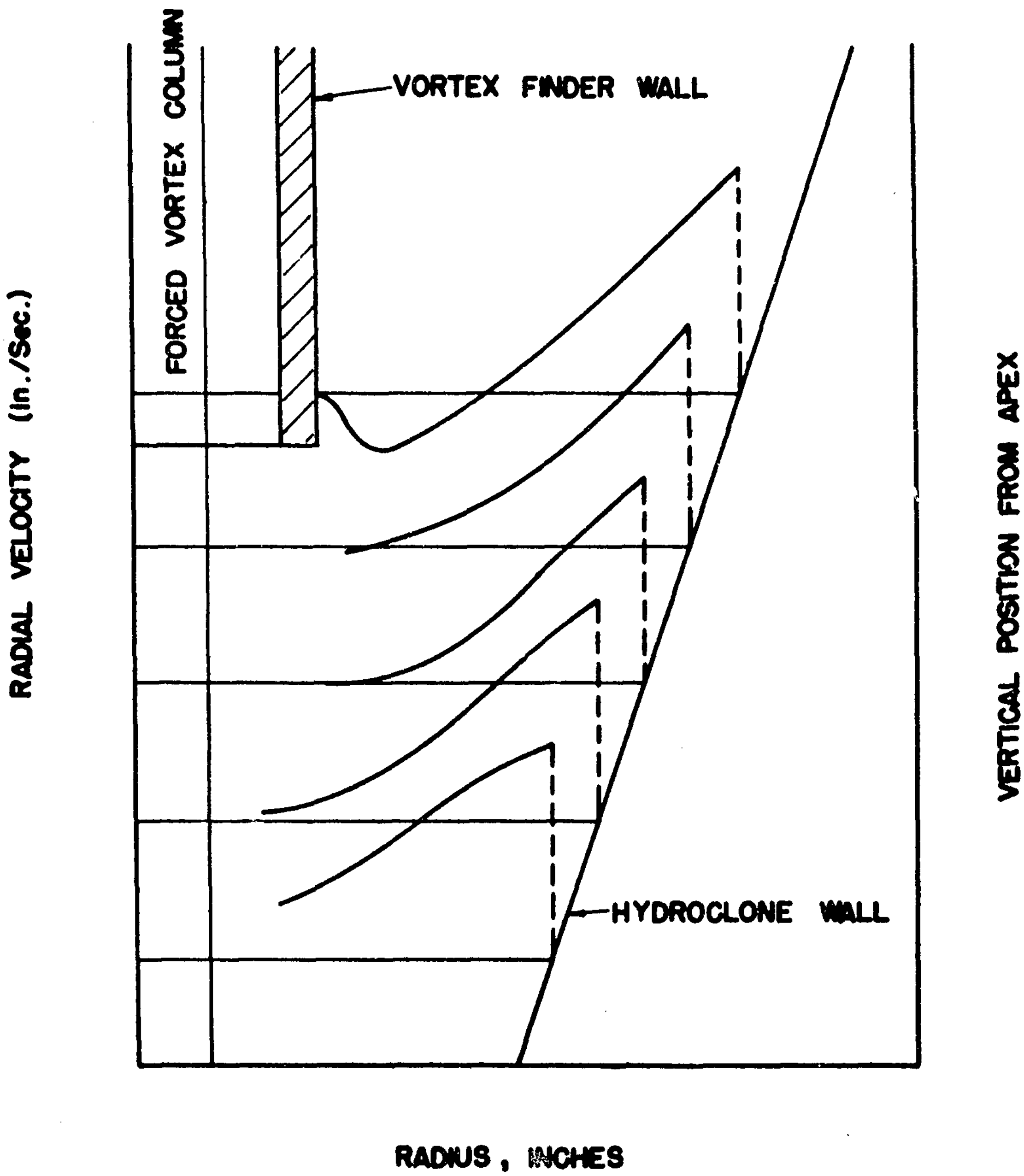

Fig. 6. Radial Velocity Versus Radius in a Hydroclone. (The curves are referenced to their respective zero datum by dash lines.)

2. Particle Behavior

The particles entrained in the liquid are influenced by the fluid velocities and the inertia forces. Due to the drag characteristics of the fluid upon the individual particles, the fluid flow patterns within the vortical field affect the ultimate particle destiny. However, the centrifugal force on the particle opposes the radial drag effects of the fluid and tends to restrain the particles from moving toward the axis of the cone. The centrifugal force is an inertia effect created by the mass of the moving particle desiring to travel in straight paths. This centrifugal force can be expressed by the equation

$$F_c = C_1 D^3 (\rho_s - \rho_L) \frac{V_t^2}{R} \qquad \text{Eq. 3}$$

in which C_1 = constant
D = particle diameter
ρ_s = density of particles
ρ_L = density of liquid
V_t = tangential velocity
R = radius of cone.

The effectiveness of the hydroclone depends significantly upon the generation of high centrifugal forces. From Eq. 3, it can be verified that high centrifugal forces will result from having

(a) large particles
(b) very dense particles
(c) low specific gravity liquids
(d) high tangential velocities
(e) small radius.

The radial velocity of the fluid reduces the separation effectiveness of the hydroclone. This reduction stems from the drag force resulting from the fluid attempting to drag the particle along with the moving stream. The drag force can be described by the relation

$$F_D = C_2 \, D \, \mu \, V_R$$

in which C_2 = constant
D = diameter of particle
μ = viscosity of fluid
V_R = radial velocity of fluid.

The effectiveness of vortical separation can be enhanced by the reduction of the drag forces -- both radial and axial. This can be achieved according to Eq. 4, by having

(a) small particles
(b) low viscosity liquids
(c) low radial and axial velocities.

The size of the particle has a greater effect (3rd power) in the value of the centrifugal force than in the drag force (first power). Therefore, the larger the particle, the greater the separation efficiency. The forces acting on the particles (centrifugal and drag) establish particle equilibrium positions within the cyclonic field. These positions represent the point or radius where the drag force balances the centrifugal force. The equilibrium radii form nearly concentric imaginary cylinders inside the conical region. Particle equilibrium radii can be illustrated as shown in Fig. 7.

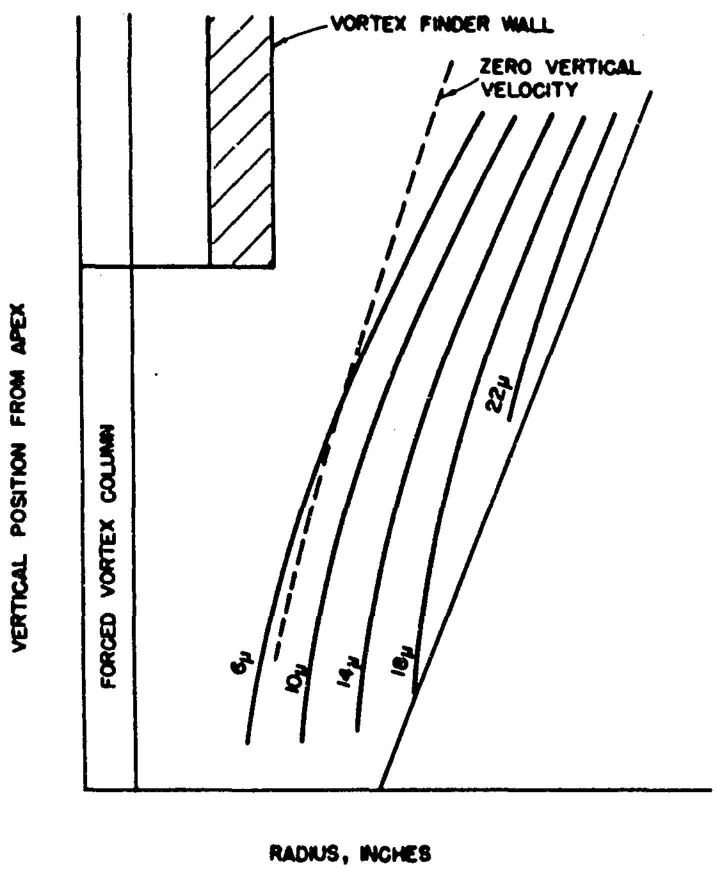

Fig. 7. Particle Equilibrium Radii.

The location of a particle equilibrium radius with respect to the zero vertical velocity envelope is a significant factor in determining whether the particle will be removed at the overflow or underflow. The zero vertical velocity envelope is obtained from a vertical velocity study such as shown in Fig. 5. Since all fluid and particles between the zero velocity envelope and the axis of the cone move toward the vortex finder, it is important to establish the proper balance point to achieve a specific separation. Particles in radial equilibrium between the zero velocity envelop and the cone wall will report to the underflow and be separated from the system fluid.

3. Separation Efficiency

The separation efficiency is defined as the fraction of the particles entering the conical section which report to the underflow. Due to the complex flow patterns within the conical section which give rise to uncertain trajectories of the particles, a rigorous solution for separation efficiency is difficult. However, the establishment of the zero radial velocity envelope provides the theoretical basis for the separation efficiency.

A particle in equilibrium on the zero radial velocity envelope has a 50% chance of reporting to the overflow and a 50% chance of being separated. A particle of this size is referred to as a D_{50} particle. A number of empirical relations have been proposed to define the D_{50} size particle. For the purposes of this discussion, the D_{50} value can be given as a function of the associated parameters as follows:

$$D_{50} = f_1\left(r_c^{\,n}, \frac{1}{\sqrt{Q}}, \frac{1}{\sqrt{\rho_s - \rho_L}}, \sqrt{\mu}, \sqrt{\tan\frac{\varphi}{2}}\right) \qquad \text{Eq. 5}$$

in which r_c = maximum radius of conical section
n = empirical value
Q = flow rate
ρ_s = density of particle
ρ_L = density of liquid
μ = viscosity of liquid
φ = included cone angle.

The separation efficiency of a $D_{50\%}$ size particle is 50%. Particles having various sizes different from the $D_{50\%}$ size will have correspondingly different efficiencies. A reduced efficiency curve is generally developed to present the separation efficiency as a function of the ratio of particle size to $D_{50\%}$. Such a curve is constant for a given hydroclone. A typical reduced efficiency curve is shown in Fig. 8. Since the reduced efficiency curve exhibits the separation efficiency

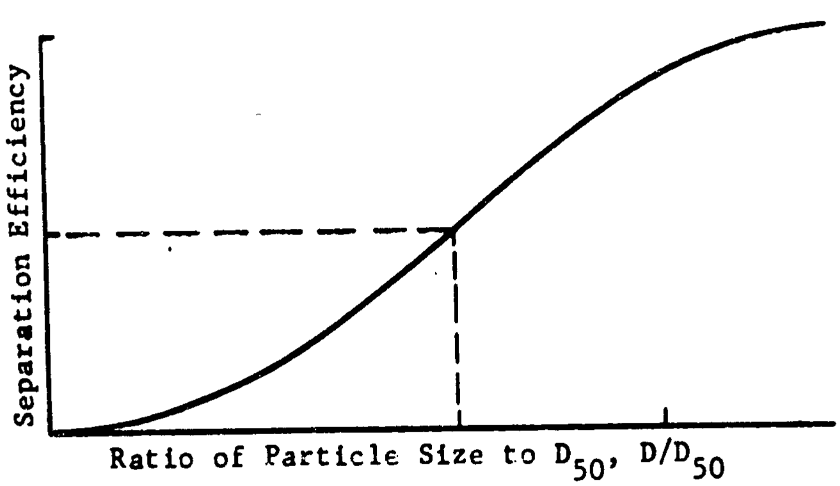

Fig. 8. Typical Reduced Efficiency Curve.

of a particular hydroclone configuration, with a given fluid medium, and with fixed operating conditions, the calculation of the $D_{50\%}$ point permits the establishment of the hydroclone efficiency for any other particle size with all other parameters held constant. For example, say the $D_{50\%}$ size is 10 microns for a given hydroclone, flow rate, temperature, fluid, etc., -- for a $D/D_{50\%}$ of .7, Fig. 8 shows that the separation efficiency for a 7 micron particle is approximately 25%. Similarly, a 12 micron particle would have about a 70% chance of being separated by the hydroclone being considered.

4. Pressure Drop

The pressure drop across the hydroclone is the sum of three associated terms:

(a) Pressure drop across the inlet.
(b) Pressure drop across the vortical field.
(c) Pressure drop across the outlet section.

The ultimate problem in optimizing the parameters of a hydroclone (with respect to pressure drop) is to minimize the inlet and outlet pressure drops. Since the pressure drops concerned with inlet and outlet flows are boundary layer friction problems, the conventional aspects involved with orifice and conduit flow applies.

In the conical section, the pressure drop is mainly attributed to the centrifugal head loss. This loss is concerned with the pressure difference evidenced across an annular layer of rotating fluid. If the thickness of an annular layer is ΔR and the radius is R, then the pressure loss is given by:

$$\Delta P = \frac{\rho_L V_t^2}{R\ g_c} \Delta R \qquad \text{Eq. 6}$$

in which ρ_L = density of liquid

V_t = tangential velocity

g_c = gravitational conversion factor.

Many empirical relations have been proposed for predicting pressure drop in cyclonic sections. The restrictions imposed on most equations are significant when general considerations are involved. However, the following relation is consistent with the equations proposed:

$$\Delta P = K \frac{Q^2}{D_c^4} \qquad \text{Eq. 7}$$

in which K = constant
Q = flow rate
D_c = maximum diameter of cone.

For a given hydroclone, Eq. 7 can be illustrated as shown in Fig. 9.

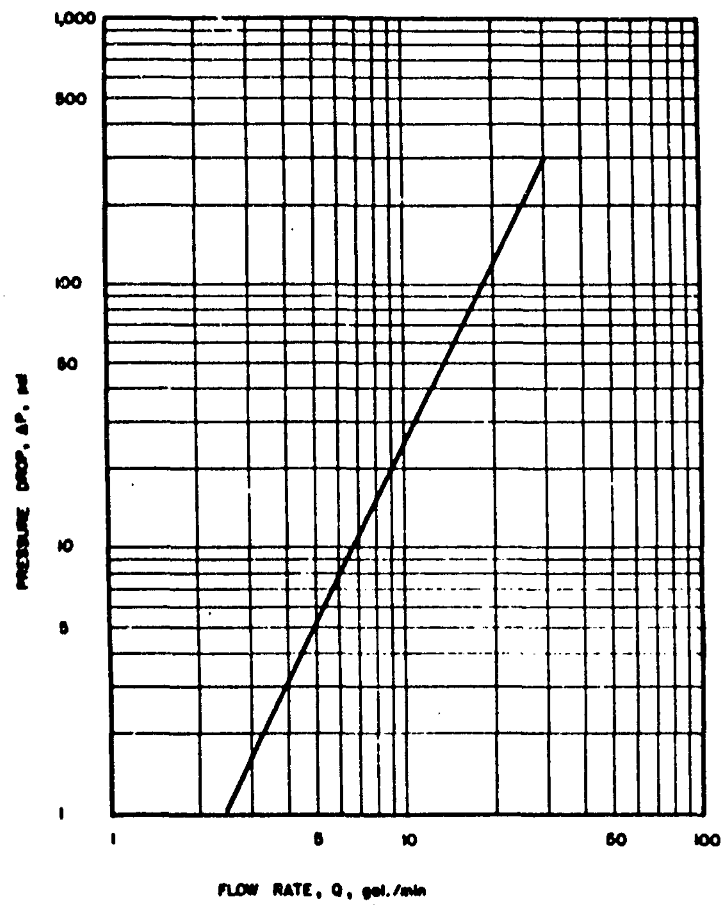

Fig. 9 Typical Pressure Drop Versus Flow Rate Curve for Conical Section

The dynamics of cyclonic flow as presented herein have revealed many of the fundamental concepts of hydroclone operation. Although a more rigorous approach could have been employed, the objectives of the section would not have been satisfied. Many of the ideas were purposely oversimplified in order to insure that an adequate foundation has been established for future presentations.

E. CHARACTERISTIC CURVES OF HYDROCLONES

The basic concepts of vortical flow have been presented in Section II-D. In accordance with these concepts, it can be recognized that the separation efficiency of a hydroclone is dependent upon four general factors:

(a) Fluid properties
(b) Particle properties
(c) Flow parameters
(d) Hydroclone parameters

In order to relate the effects of these factors to the separation efficiency of the hydroclone, characteristic curves are desirable. The curves presented herein are included to exhibit trends and have no relation to absolute values.

1. Effects of Fluid Properties

The fluid properties which reflect on the separation efficiency of a hydroclone are:

(a) Viscosity of liquid
(b) Density of liquid.

The curves displaying the corresponding trends are shown in Figs. 10 and 11. Since the temperature of the system varies approximately inversely as the viscosity, the inverse of the curve in Fig. 10 can be accepted for the fluid temperature curve.

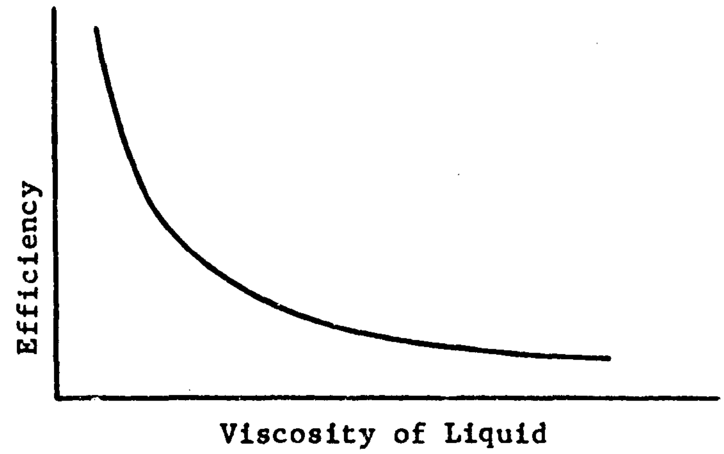

Fig. 10. Efficiency Versus Viscosity of Liquid.

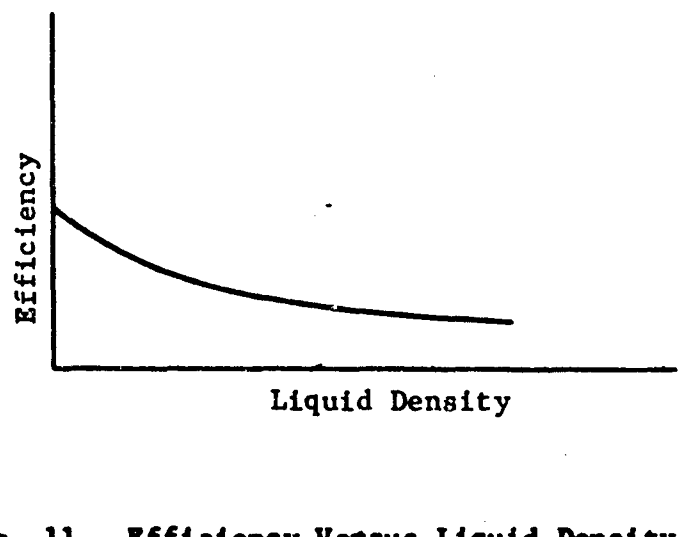

Fig. 11. Efficiency Versus Liquid Density.

2. <u>Effect of Particle Properties</u>

The properties of the particles affecting hydroclone separation efficiency are:

(a) Density of particles
(b) Diameter or size of particles.

The curves showing the effect of particle properties on separation efficiency are shown in Figs. 12 and 13.

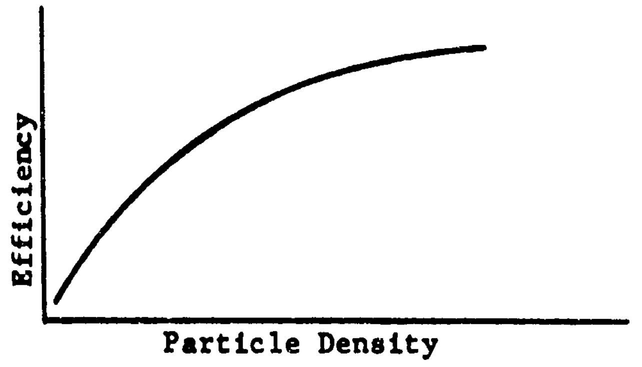

Fig. 12. Efficiency Versus Particle Density.

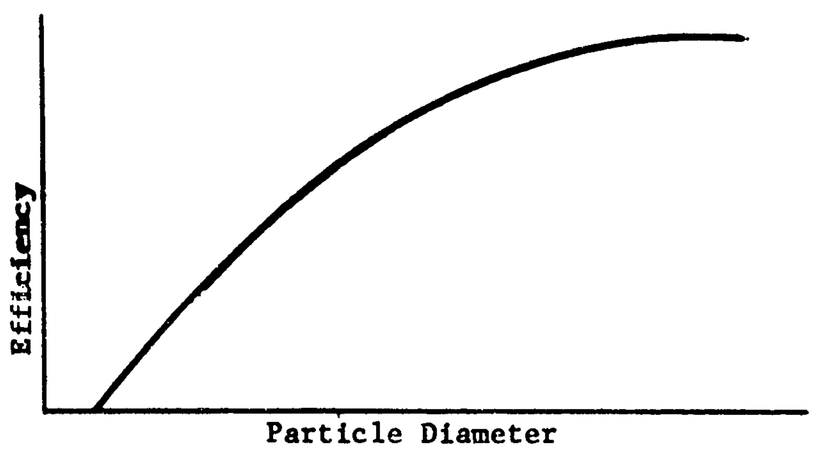

Fig. 13. Efficiency Versus Particle Diameter.

3. <u>Effect of Flow Parameters</u>

The flow parameters affecting the hydroclone separation efficiency are:

(a) Flow rate
(b) Tangential velocity
(c) Pressure drop across hydroclone.

The curves illustrating the effects of these flow parameters are shown in Figs. 14, 15, and 16.

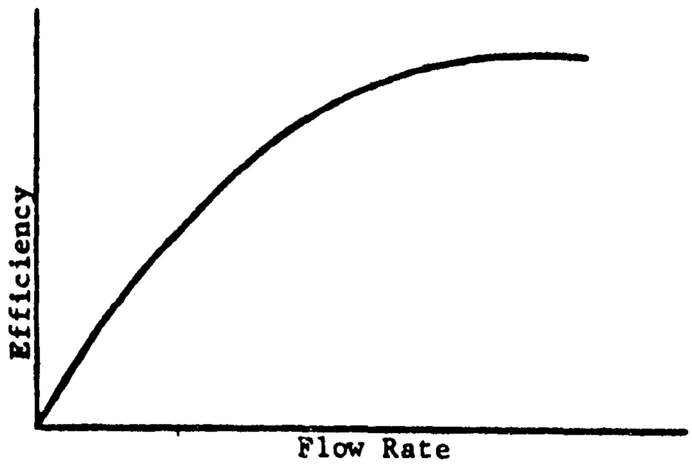

Fig. 14. Efficiency Versus Flow Rate.

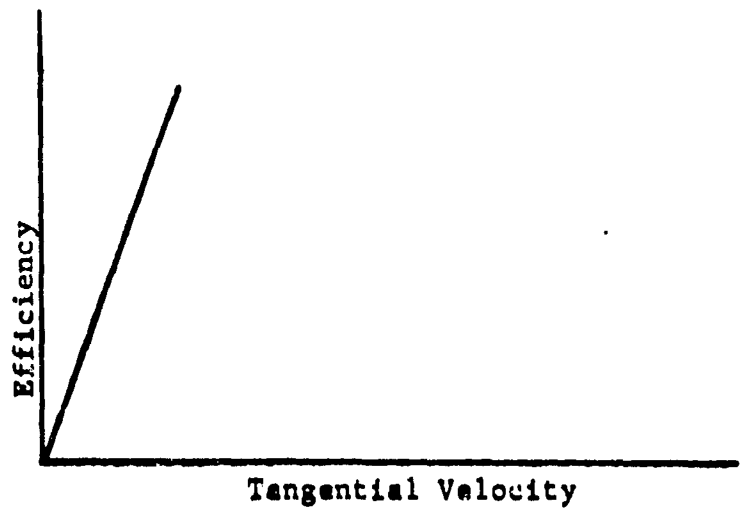

Fig. 15. Efficiency Versus Tangential Velocity.

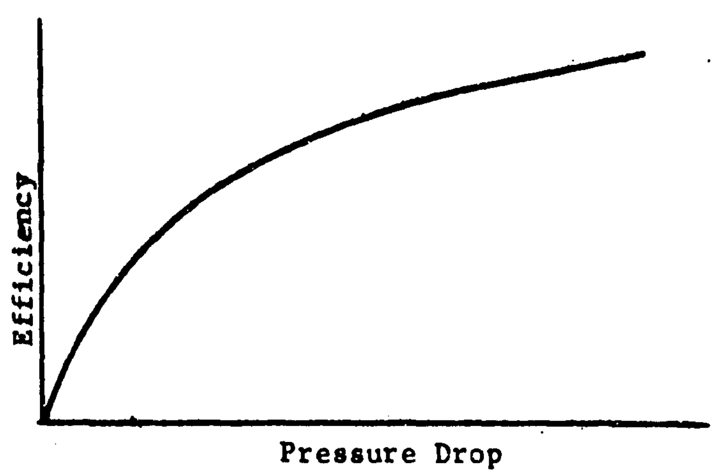

Fig. 16. Efficiency Versus Pressure Drop.

4. **Effects of Hydroclone Parameters**

The hydroclone parameters affecting the separation efficiency of the unit are too inter-related to be presented in a simple form. However, the three parameters of special concern which can be characterized are:

(a) Diameter of hydroclone (maximum diameter of cone)
(b) Diameter of inlet
(c) Cone angle.

Based on the results of studies presented in the literature, the effects of the above parameters on hydroclone separation efficiency display the same trend as shown in Fig. 17.

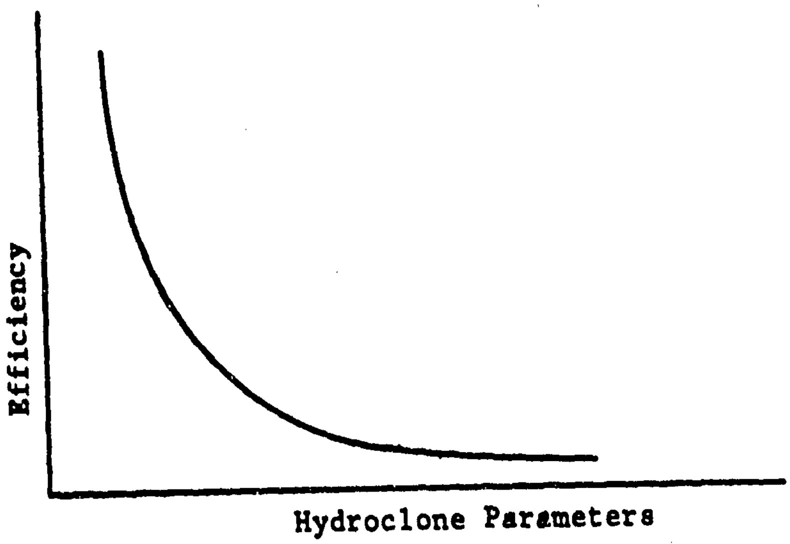

Fig. 17. Efficiency Versus Hydroclone Parameters.

SECTION III

CONTRACT INTERPRETATION AND IMPLEMENTATION

A. INTRODUCTION

The theory of operation and the methods of constructing hydroclones from existing theories dates back many years. Judging from an examination of past and present literature as compiled in Appendix I, the design of a cyclone to classify particles is becoming, to some degree, a science insteady of a pure art. Much information about hydroclone dimensions can be found in almost any literature pertinent to cyclones. However, cyclone application for the classification of particles in hydraulic oils and similar viscous fluids is not commonly found. The literature for these cyclones is scant, probably due to the fact that all cyclone parameters must be optimized as a unit for a specific set of conditions.

Recently, much interest has been generated concerning the possible use of miniature hydroclones (hydraulic cyclones) to help alleviate some of the filtration problems existing in the missile and space field. Hydroclones offer several advantages over ordinary hydraulic filters, providing the correct hydroclone configuration is found for the particular job.

Several of these advantages are an unlimited dirt-holding capacity, constant-pressure drop versus time relationship, and the relatively small size of the unit in comparison with a comparable-type conventional filter. Also, a hydroclone in a system with a companion filter would increase the life of the filter many times.

Until the present time, no one has been able to give a satisfactory theory of hydroclone operation which would allow accurate theoretical prediction of optimum design and performance. Such a theory was probably unnecessary because earlier needs were easily fulfilled by existing designs. Because of this large gap in the art, coupled with the need for a hydroclone capable of giving a low-micron separation with hydraulic fluid, a theory of operation was needed. After reviewing literature obtained while compiling a literature survey on fluid contamination, the idea of using a hydroclone in a hydraulic system was proposed by OSU project personnel in 1959.

1. Theoretical Studies at OSU

The majority of investigators have relied heavily on empirical equations and experimental data to design cyclones for new applications. Some of the more useful expressions for separation efficiency and pressure drop are found in Section II. OSU investigators felt that these expressions were not applicable to all hydroclones, since they did not apply to the cyclone units being tested with hydraulic oil. These

expressions were limited to hydroclones of a certain size, and fluids within a certain viscosity range. Therefore, it became necessary to find expressions that would apply to hydroclones in general.

Studies conducted at OSU consisted of both theoretical and experimental work. The theoretical work consisted of deriving analytical expressions to predict particle movement in the hydroclones. These studies over the past several years, have resulted in the writing of three masters theses (10, 16, 49) at OSU pertaining to hydroclone separation efficiency. In addition, a research team was sponsored by the Office of Engineering Research to determine the operating parameters of the hydroclone. From analytical expressions derived in these theses, it is possible to predict the D_{50} separation size (50% by weight separation for a particular size contaminant). An analog computer was extensively used to solve the equations involving variations of several parameters and to determine the significance of variations in the parameters. The variables in the equations were as follows: flow rate, cone angle, viscosity, particle diameter, hydroclone diameter, density of particle, and density of fluid.

The equations developed were based on the assumption that secondary or inefficient flow patterns did not exist and a particle could be removed if the centrifugal force was greater than the drag force, and sufficient time was permitted for the particle to move to the outer wall and be discharged into the underflow-collection chamber. By experimentation, the flow range was determined at which a particular size of particle was in equilbrium at the same radius as the vortex finder. Using this data, curves were constructed from which one could predict hydroclone performance. Experimental data compared favorably with these theoretical predictions except at low flow rates where the vortex patterns were irregular. The main deficiency of these equations was that they did not yield any workable equations for determining hydroclone separation efficiency in terms of the main hydroclone parameters. An expression was needed to determine the effects of changing parameters such as:

(a) inlet diameter
(b) overflow diameter
(c) underflow diameter
(d) inlet angle
(e) length of vortex finder.

Such expressions for separation efficiency and a rigorous pressure drop theory were developed in a thesis (48) at OSU by Richard Gerlach while a member of the research team sponsored by the Office of Engineering Research at OSU. As a result of his studies, it was concluded that the separation efficiency and pressure drop was accurate for the range of variables used in the tests. For other ranges of these variables (flow rate, hydroclone radius, viscosity, etc.), it was not known if the equations were accurate. The main applications of Gerlach's equations were to indicate the effect of these operational variables upon the hydroclone performance. Sufficient experimental data were needed to substantiate these relations in order that curves or tables of data could be prepared from which hydroclones could be completely designed

for new applications. In order to verify these equations, it was necessary to pursue a comprehensive experimental program which required sophisticated instrumentation and equipment.

2. Experimental Studies

The power stands and equipment used in the early studies on hydroclones at OSU were very basic in construction, and as a result, very limited in operation. The first hydraulic system consisted of an auxiliary power stand and a metal frame rack to hold the test components. The stand delivered 15 GPM at 2,000 psi and had provisions for varying the test-fluid flow and temperature. The contaminant injection system consisted of a high-pressure handpump and a small reservoir containing a contaminated slurry. Glass beads were used as the principal contaminant, and the efficiency of a hydroclone was determined by observing the number of beads collected on upstream and downstream Millipore filter pads. The absolute separation size for these first experimental tests with the hydraulic oil using glass beads was 50 microns for a one-inch hydroclone designed from empirical relations obtained from the literature. Details of these tests can be found in Fluid Contamination Project, Report Number Two (45). Following the completion of these tests, a contract for the study of fluid contamination and hydroclones was sponsored by Tinker Air Force Base.

Included in this contract were provisions for constructing a semi-automatic power stand for the testing of hydroclones. Midway in the program, personnel at Tinker Air Field felt that it was necessary to concentrate on the evaluation of conventional filters, and the hydroclone project was discontinued. However, the power stand was completed and analytical expressions were derived prior to the cancellation of the hydroclone project. The Office of Engineering Research at OSU maintained that the theoretical and experimental studies on hydroclones should be continued to determine new applications for the hydroclones; and they assumed the sponsorship of this study.

A picture and schematic drawing of the semi-automatic stand are shown in Figures 18 and 19. This stand was capable of producing 20 GPM at 2,000 psi, with variable flow rate, and had a manual temperature control for the test fluid. The injection system consisted of a hydraulic cylinder pushing a slurry of contaminant into the main system by the use of a precharged accumulator. An automatic timer allowed flushing of the cylinder for a specified time and then the cylinder retracted for another injection. Sampling valves were provided before and after the hydroclone to obtain samples for evaluation. A Coulter Counter was used to determine the number and size of particles before and after the hydroclone. Results of these tests can be found in a master's thesis (16) written by R. E. Bose at OSU. As a result of these efficiency tests, Air Force personnel requested that a demonstration of the OSU hydroclone be conducted on a ground-support hydraulic cart at Castle Air Force Base. Results of these tests, evaluated and reported by the Air Force, showed that in a period of 10 minutes, the gravimetric weight of the fluid samples was reduced from 5.0 mg/liter to 1.7 mg/liter.

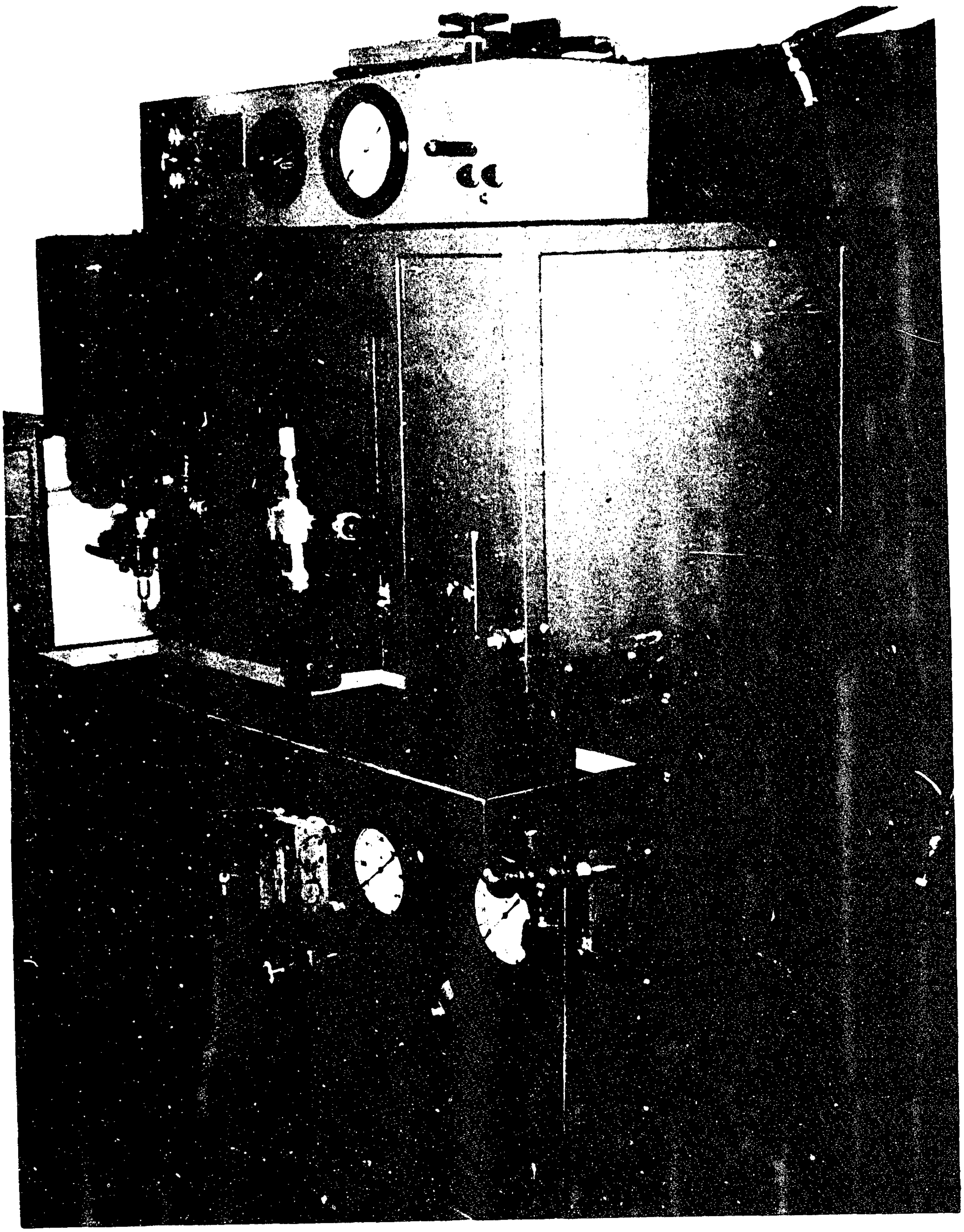

Fig. 18. Semiautomatic Power Stand

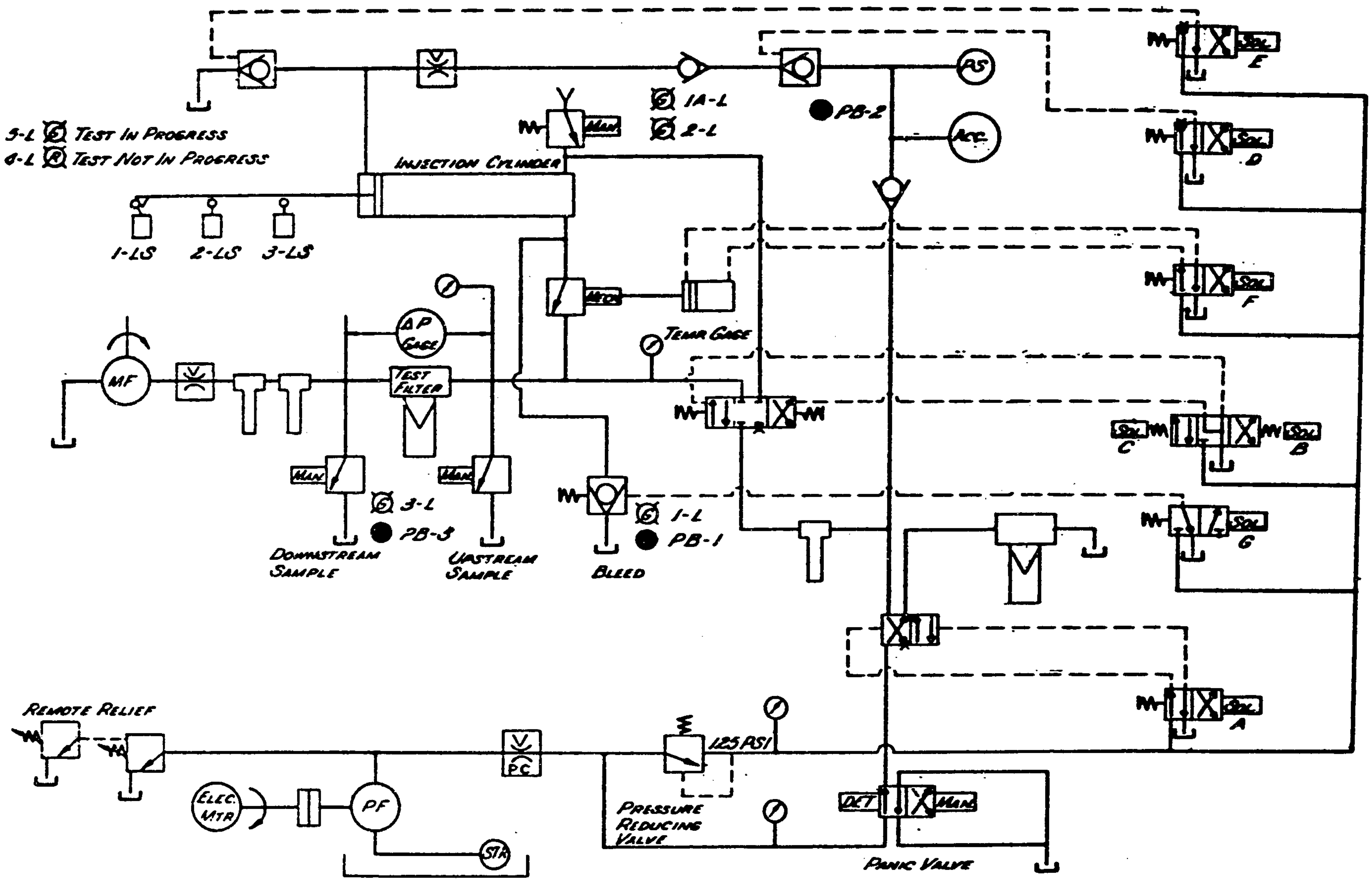

Fig. 19 Hydraulic Schematic for Semi-Automatic Power Stand

Consequently, personnel from OSU and Aeronautical Systems Division agreed that a comprehensive investigation be initiated to establish design criteria for hydroclone prototypes to be used on ground-support equipment. For such a program, OSU would need to build appropriate power stands to complete the testing necessary to fulfill the requirements set forth in the Contract Work Statement with Wright Air Development Center.

B. GENERAL FACILITY REQUIREMENTS

The equipment necessary to fulfill the requirements for optimizing hydroclones for Air Force ground-support equipment consists of three power stands and companion equipment. Power Stand No. 1 (shown in Fig. 20) is to be used for efficiency tests. It will be necessary to check the size and number of particles in the fluid before and after a hydroclone test section to determine the absolute rating of a hydroclone. The D_{50} size (50% by weight to overflow) will also be determined from the particle counts. To be able to optimize a hydroclone for the specific application, this stand must be capable of delivering 30 gpm at 2,000 psi continuous operation. The flow rate must be adjustable from 0 to 30 gpm so that the flow rate can be controlled as another hydroclone parameter is varied. A temperature controller must be used to maintain the temperature constant throughout the test period. A means of obtaining sample values by inline sampling and bottle samples must be provided on the stand. Hydraulic motors with magnetic pickups will be used to determine flow rate.

It was deemed necessary to have a continuous injection system for the efficiency stand, so that samples of hydraulic fluid could be monitored over long periods of time, enabling the experimenters to acquire representative contamination data from the system. For a continuous type injection system, a gear pump will be used to inject a slurry of contaminant into the main fluid stream during operation. A constant injection rate over a period of minutes will provide a uniform source of contaminant for sampling and evaluation. The sample of fluid could either be collected in bottles, filtered, and the contaminant observed under a microscope to determine the type and size of particle, or inline sampled. The main type of sampling to be used should be inline. Inline sampling would consist of taking a portion of the fluid and continuously checking the size and distribution of the contaminant upstream and downstream from the hydroclone, thereby eliminating some errors of sampling. Particle counters would sample the fluid at relatively high pressures and evaluate the sample during continuous flow operation.

Data from Power Stand No. 2 (shown in Fig. 21) will be used to determine the optimum dimensions of a unit by having pressure taps at strategic places in the hydroclone and determining the best possible configuration for the particular hydroclone. From these pressure-tap readings, the most efficient type of nozzle(s) for the hydroclone will be determined. The maximum tangential velocity can be determined from the pressure drop across the cyclone section, and the most efficient overflow nozzle can be determined from the pressure drop across the overflow nozzle. The most efficient nozzle is defined as that which produces the smallest pressure drop in a hydroclone for a given flow

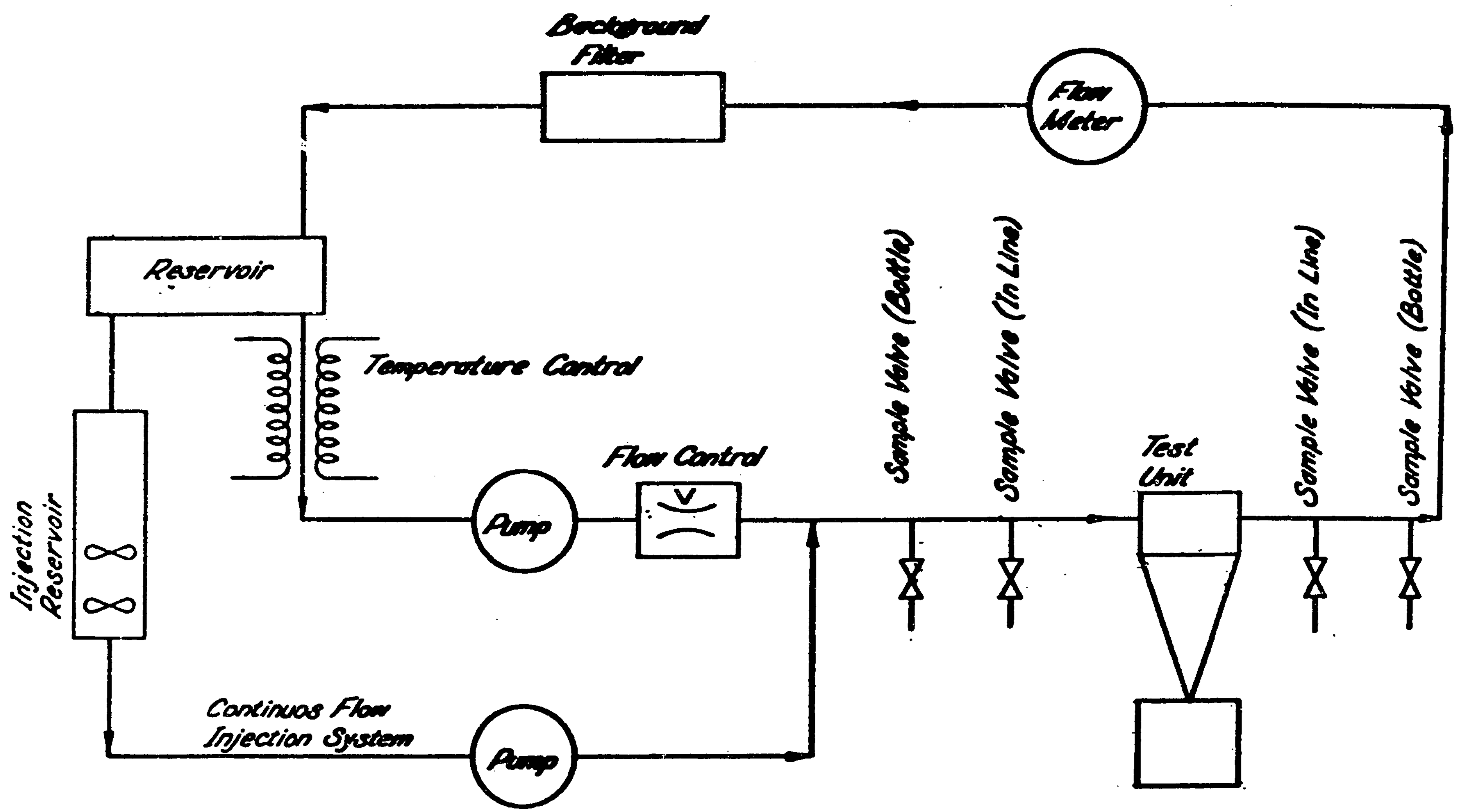

Fig. 20 Schematic Circuit of Efficiency Stand

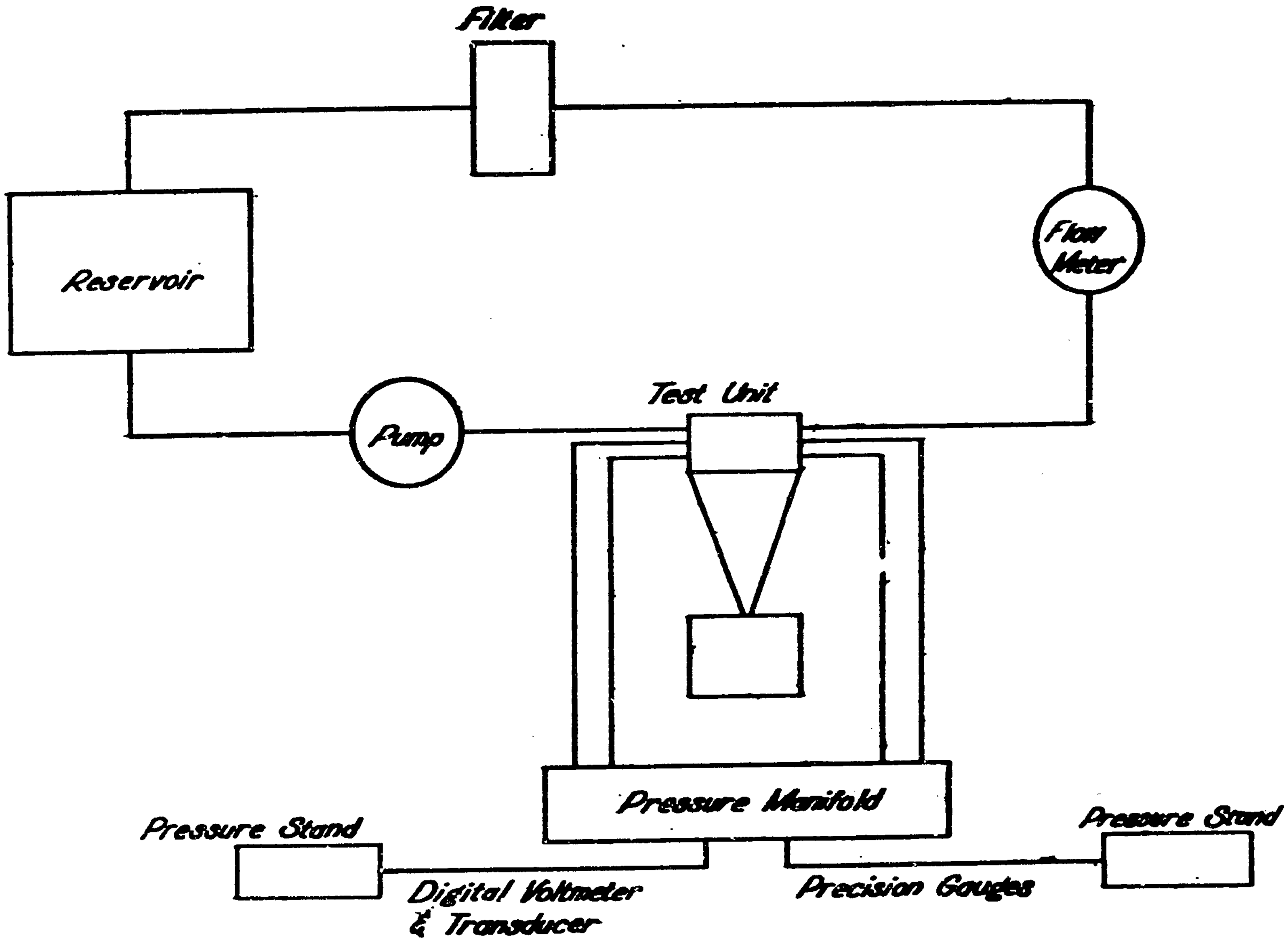

Fig. 21 Schematic Circuit of Pressure Drop Stand

rate. The power stand shall have appropriate outlets for the extraction of sample fluid for inline or laboratory evaluation. A magnetic pickup will also be used in conjunction with a positive displacement motor to determine flow rate. A low-pressure and high-pressure transducer will be used to obtain differential pressure measurements.

Power Stand No. 3 (shown in Fig. 22) will be designed and constructed to test fluids of various density, temperature, and viscosity. The components of this stand must be constructed of materials that are compatible with water and other non-lubricating liquids which may corrode or rust conventionally used materials. The test program shall consist of checking each parameter by pressure-drop tests and efficiency tests. Data from pressure-drop tests will be used to determine tangential velocities, overflow energy recovery, nozzle efficiency versus pressure drop. For each parameter, curves of efficiency will be plotted to determine the optimum dimension. Large increments of the parameter dimension will be taken to bracket the optimum dimension. Subsequent tests will further reveal the optimum dimension by taking smaller increments about the suspected optimum size. All other parameter dimensions will remain constant when a particular dimension is being varied. Flow rate will be the operating or varying parameter for each test.

The parameters to be varied in the program are as follows:

(a) D_o - diameter of overflow
(b) D_c - diameter of cyclone (major diameter)
(c) D_i - diameter of inlet
(d) D_u - diameter of underflow
(e) L_1 - length of cyclone cylindrical section
(f) L_2 - length of vortex finder
(g) φ - included angle of cyclone
(h) β - angle of inlet nozzles
(i) N - number of inlet nozzles
(j) N_p - placement about circumference
(k) L_{cc} - length of collection chamber
(l) D_{cc} - diameter of collection chamber
(m) γ - angle of subcone
(n) L_{sc} - length of subcone

Efficiency tests are to be conducted on the optimum hydroclones whose dimensions are set from pressure-drop data. Inline particle counters will determine the number and size of particles in the system before and after the hydroclone. Additional efficiency checks will be made on hydroclones by varying the parameters from the optimum dimension, as a confirmation on the optimization of dimensions. A-C Test Dust will be used as the standard contaminant for all tests. The collection chamber will be cleaned after each injection of contaminant to insure that previous tests have no effect on the efficiency test.

The purpose of this test program is to verify OSU hydroclone equations and establish design criteria required for the fabrication of miniature hydroclones to satisfy Air Force requirements for decontaminating hydraulic fluids to be used in conjunction with existing ground-support equipment.

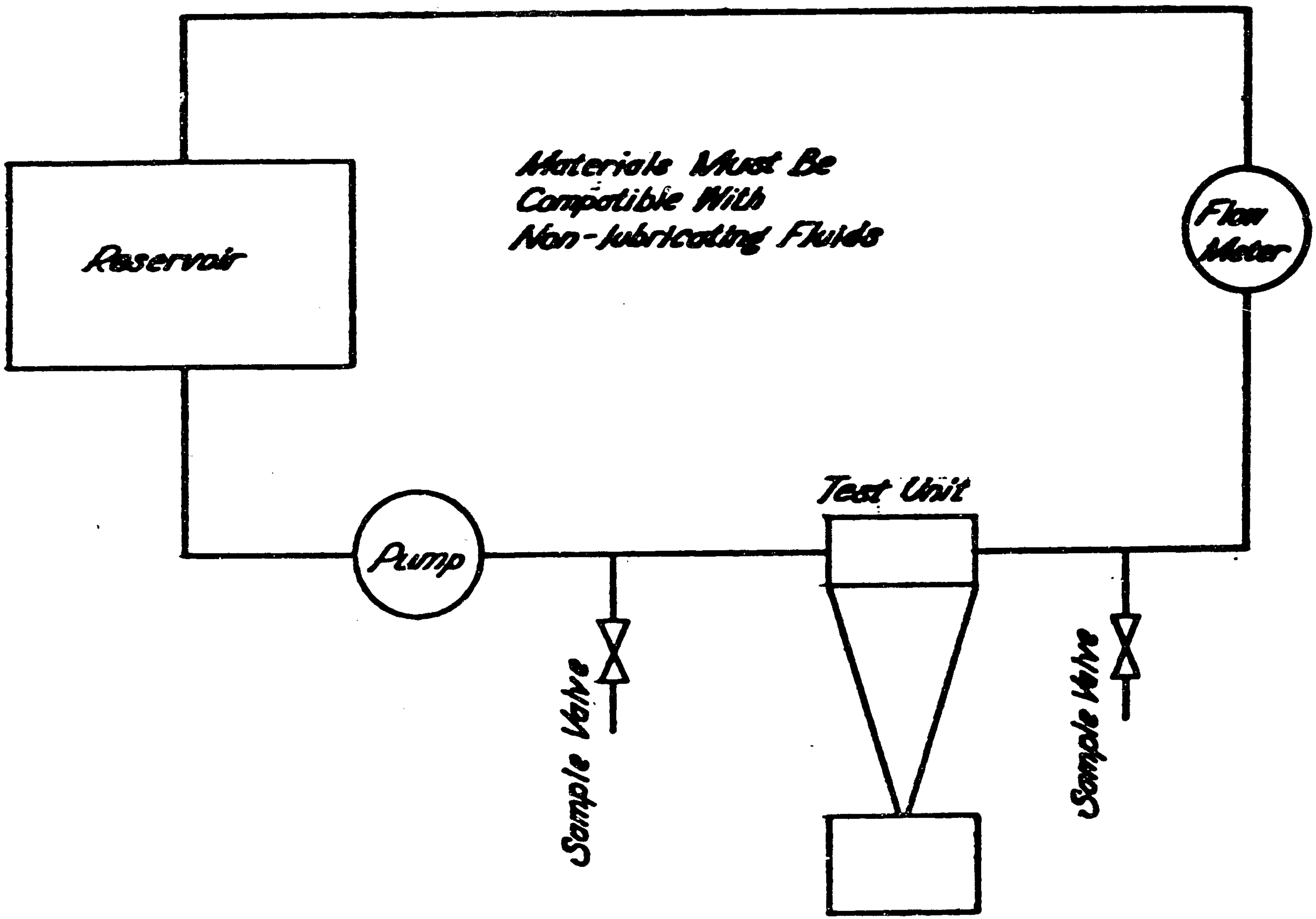

Fig. 22 Schematic Circuit of Non-Lubricating Fluid Stand

C. GENERAL STUDY REQUIREMENTS

The three power stands, to be designed and constructed by OSU personnel, will satisfy the requirements "a," "b," and "c," as set forth in the Statement of Work of the program, from the standpoint of equipment necessary for testing. Section "a" states, "An auxiliary hydraulic power stand shall be designed to facilitate fluids other than hydraulic fluid (MIL-F-5606) for complete evaluation and study on different hydroclone configurations, fluids, pressures, flow temperatures, etc." Section "b" requires, "An investigation will be made to determine the effects of variations in fluid density, fluid temperature, fluid viscosity, and hydroclone dimensions and separation efficiencies for various values of pressure drop at predetermined flow and pressures." Section "c" provides that "Subsequent to compilation of design data resulting from the investigations under paragraph "b" an investigation shall be conducted to determine the effects of transient flow on separation efficiency resulting specifically from zero to full flow as encountered in ground-support equipment."

An auxiliary stand will be required to evaluate the cone materials set forth in section "e" of the Statement of Work. Section "e" states, "The investigation shall include an evaluation and section of cone materials that will provide reliable and efficient service." These tests will determine what material will be the best for the cone, inlet and overflow nozzles. A hydraulic ground-support stand such as the MJ-1 would be ideal for these tests. Cones constructed of aluminum, anodized aluminum, urethane, and ceramics will be tested to determine which of these materials is the most suitable for the particular application. The test will consist of constructing blind cones (cones with no underflow) and injecting a measured quantity of contaminant into the system. The particles will then remain in the cone because of no underflow opening and, therefore, will rotate with the fluid. All tests will be performed at the same flow rate, temperature, and pressure drop. The dimensions of the hydroclone will remain constant for all tests. The cone will be observed at the end of a predetermined time to ascertain if erosion is taking place, and if so, to what degree. A filter will be placed downstream in the system to protect the components of the system in case of a failure leading to dumping of the contaminant into the main system from the hydroclone.

Tests to determine the effects of transient flow on separation efficiency as flow is varied from zero to full flow, as encountered in ground-support equipment required by section "c," will be evaluated. The test will be conducted using Power Stand No. 2. A slurry of contaminant will be added to the collection chamber and the flow varied from zero to full flow. Samples of fluid before and after the hydroclone will be taken to determine what size particles are rejected from the underflow chamber. A filter will be put inline to keep the background particles to a minimum so that any particles counted on the downstream side will be from the hydroclone collection chamber. If the experimental data indicates that particles of size greater than the absolute separation size are rejected to the overflow from the collection chamber at the point of saturation of the collection chamber, a

system of baffles will be developed. A visual observation of the collection chamber will be made in an attempt to determine inefficiencies due to flow patterns for intermittent and continuous flow operation. The amount of contaminant added will be recorded to determine when the collection chamber requires attention, thus satisfying section "f" of the Statement of Work.

Section "f" states that "The investigation shall include a means of determining when the hydroclone collection chamber requires attention. A determination shall be made on optimum size of dirt holding capacity."

The results of the efficiency tests of the optimum hydroclone shall determine the absolute rating of the hydroclone for AC Test Dust or any other particles of equal or greater density. This will satisfy section "d" of the Statement of Work. Section "d" provides that "An absolute (micron) separation rating shall be established subsequent to compilation of data from paragraph "c." This shall include the rating, if the rating differs under varying flows."

The ideas presented in this report are an interpretation of the Air Force Contract AF 33(657)-9958 by Oklahoma State University project personnel. The supplemental equipment, which was procured under this contract to conduct a comprehensive study, was of a specialized nature especially adapted for contamination analysis.

SECTION IV

THE FACILITIES

A. INTRODUCTION

The general requirements for the implementation of the Hydroclone Project under Air Force Contract AF 33(657)-9958 necessitated the acquisition and construction of equipment as set forth in the previous section. This section describes such facilities that have been acquired and fabricated to accomplish the objectives of the hydroclone research project, and has been divided into the general classifications of tests that are to be conducted with the equipment necessary to perform these tests. The five classifications of tests are efficiency tests and pressure drop tests, in which hydraulic oil (MIL-F-5606) test fluid is used, and parameter tests employing non-lubricating fluids, and materials tests. To perform these tests, three power stands were constructed; one to determine separation efficiency, one for the pressure drop, and the other to study the effects of changing fluid properties on a hydroclone's performance. The two hydraulic oil power stands are also applicable to the materials test program discussed in Section IX. In addition to these power stands, three auxiliary stands were constructed to be used in combination with the power stand to permit the injection of contaminant into the test system, the evaluation of the particle count in the system after injection, and to measure the pressure drop across sections of the hydroclone. The combined applications of the power stands and the auxiliary stands allowed OSU personnel to complete the general classification tests.

For the conduction of these tests, special hydroclone housings were constructed to facilitate the variation of hydroclone parameters. The final design and construction of these hydroclone housings which enable quick and easy changing of parameter dimensions are also discussed in this report.

B. SEPARATION EFFICIENCY TEST FACILITY

The most direct method of evaluating the ability of a hydroclone to remove contaminant from a fluid is to compare the contaminant level of the fluid upstream of the unit with its contaminant level downstream. However, before these tests could be initiated, there were three basic requirements. 1) First, a simulated hydraulic system containing a hydroclone was necessary; 2) then, to allow regulation of the amount of contaminant added to the system, a contaminant injection system was needed; and 3) in order to measure the contaminant level in the fluid stream prior to entering and after leaving the hydroclone, it was essential to provide a means of evaluating the fluid stream for contaminant.

The power test stand described in this section provides the means of circulating fluid for the tests. This stand contains the basic

system for all hydroclone evaluation tests conducted on this project. It simulates a hydraulic system which includes a test hydroclone unit.

Contaminants are introduced into the test system in order to provide the hydroclone with representative particles to separate. The injection stand injects contamination in a slurry form ahead of the upstream sample point at a constant rate. This injection is initiated before samples are taken and continued during the sampling period to maintain a uniform contamination level. Flow rate, pressure drop, and viscosity are maintained constant by the power stand. Contamination level is controlled by the injection stand, and steady state conditions are thereby assured during the separation efficiency tests.

Measuring the contaminant that is present in a fluid stream by conventional methods is difficult, tedious, and inaccurate. Normally, a sample of the test fluid is removed from the system and optically evaluated in a clean room. This operation is time consuming, and the possibility of contaminating the sample is present in spite of meticulous handling. Measuring the contaminant in a stream directly (by inline techniques) is more satisfactory and accurate.

Various methods are used to measure the degree of contamination of a given fluid. The most common instrument used is the microscope. Basically, the microscope method consists of filtering a sample of fluid through filter paper with rectangular grids marked on it, and counting the particles within one square, using a microscope. Particles are counted and sized with the aid of a micrometer state eyepiece. This method is slow, evaluation of a single sample requiring about one hour, and is subject to errors of 20% (45). Other techniques are similarly tedious and imprecise.

Since a large number of tests were required to determine which hydroclone configuration would yield the highest separation efficiency, the method of determining contamination level had to be reasonably fast and not subject to external effects. The technique devised to accumulate contamination data on this project minimized the problems discussed above to the greatest degree possible. The method selected is fast (about 5 minutes per test), relatively independent to operator skill, and at least as accurate as the microscope method (101). Furthermore, the samples taken are confined within the system and never exposed to the air or handled. Thus, the effects of airborne contamination, particularly severe in the range of 5 to 20 micron particle sizes, is eliminated.

Fig. 23 is a diagram of the facilities used to determine the ability of various hydroclone configurations to separate contamination particles from hydraulic fluid. The test requirements are satisfied by continuously and simultaneously sampling upstream and downstream of the test unit and counting the particles in the sample fluid. This is a direct method of evaluating a hydroclone's performance. All precision equipment used for this study was calibrated in the manner specified by the respective manufacturer and was calibrated in time intervals conforming to the equipment requirements.

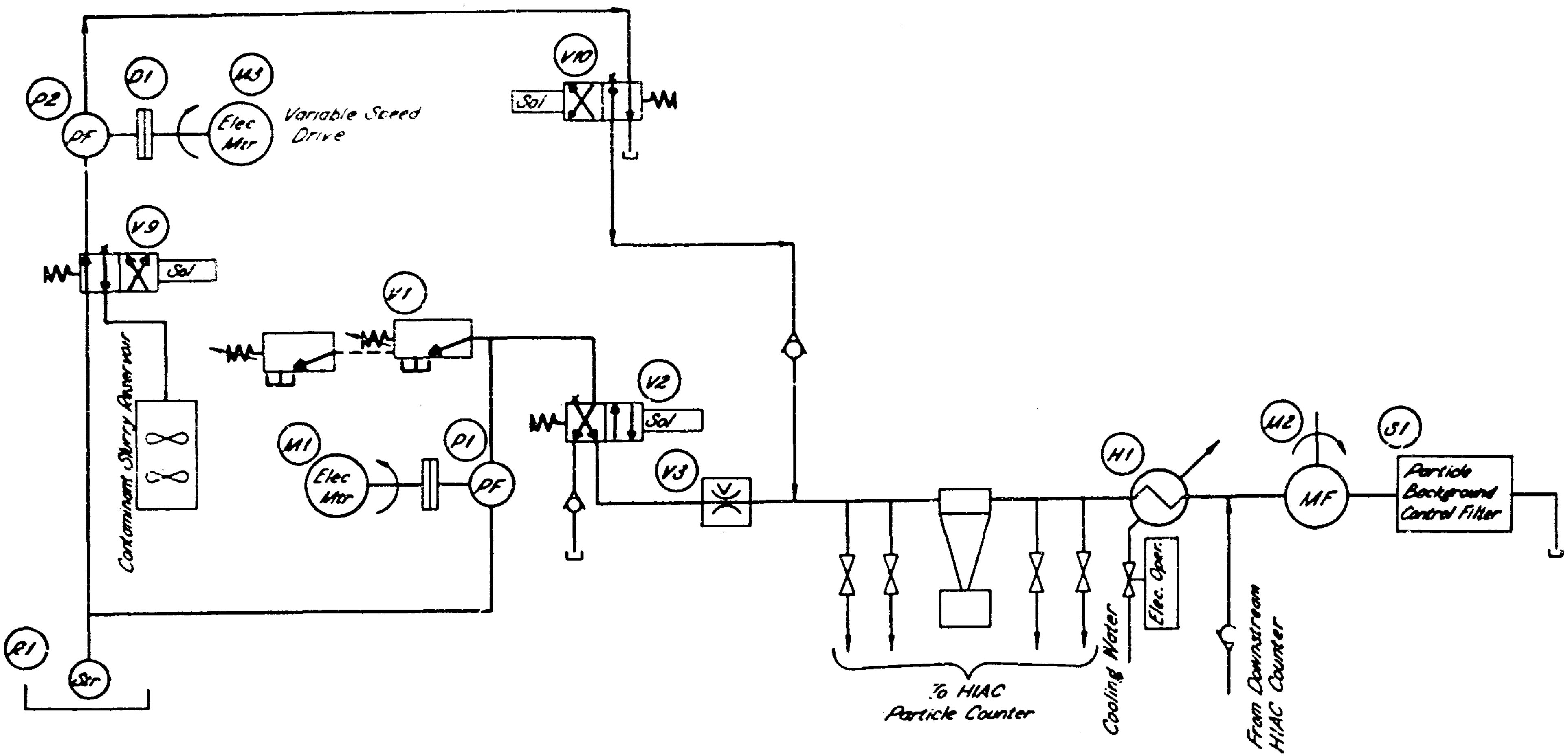

Fig. 23. Schematic Pipe Diagram of the Separation Efficiency Test Integrated with the Contaminant Injection Stand Circuit.

1. Power Test Stand

Circulation of fluid through the hydroclone is provided by a power stand (See Fig. 23) which consists of a pump, a reservoir, flow metering equipment, a control panel, and a mount for the test hydroclone. A list of the major equipment and the respective manufacturers can be found in Appendix B. The reservoir (R_1) is an elevated tank with a capacity of 120 gallons and was designed to have all return lines located below fluid level to reduce aeration. Fluid from the reservoir is gravity fed to the circulation pump (P_1) which has a capacity of 30 gpm at 2000 psi. The pump is a positive displacement type gear pump and was selected because its constant delivery characteristic provides a stable, easily regulated flow of fluid into the system (43). The pump incorporates pressure-compensated wear plates which reduce the side clearance of the housing and hence reduces slippage flow. The pump is driven by a 40 horsepower, three phase, 1767 rpm electric motor (M_1).

From the pump, fluid flows through a pilot-operated pressure relief valve (V_1) which can be remotely adjusted on the instrument panel. A solenoid-operated, 3-way flow diverting valve (V_2) receives the fluid from the relief valve and diverts the fluid from the test section to the reservoir in the event a leak or failure downstream should occur. In the de-energized position of the solenoid valve, fluid flows into a diverting valve and back to the reservoir; whereas in the energized position, fluid flows into the test section through a flow control valve (V_3). The flow control valve passes some of the total stream into the test section, depending on the requirements of the test, while the remaining fluid is returned to the reservoir. As previously mentioned, 30 gpm are available from the pump; hence, the flow control valve governs a flow range of 0-30 gpm through the test section -- the operating range of the MJ-1 hydraulic cart for which the prototype hydroclone is being optimized.

The test section of the power stand shown in Fig. 24 consists of a panel which provides a mounting for the test hydroclones, pressure gages (G_1, G_2) upstream and downstream of the unit, a temperature indicator (T_1), and taps for collecting discrete or continuous fluid samples. The fluid which leaves the test section encounters a back pressure valve. This valve, a standard ball valve, is used to maintain a high enough back pressure on the hydroclone to prevent flashing of the fluid. A heat exchanger (H_1) is placed in the return line of the system to cool the hydraulic fluid so that over-heating, and consequent possible fractionation, of the oil is avoided. A hydraulic gear motor (M_2), installed in the return line, monitors the flow rates. The fluid is filtered prior to termination in the reservoir to remove contaminant from the hydraulic system so this contaminant will not interfere with succeeding tests. The filter (S_1) has a nominal separation rating of 1/2 microns.

2. Electrical System for Power Test Stand

Fig. 25 is a diagram of the electrical control system of the separation efficiency hydraulic fluid power test stand. Three sets of

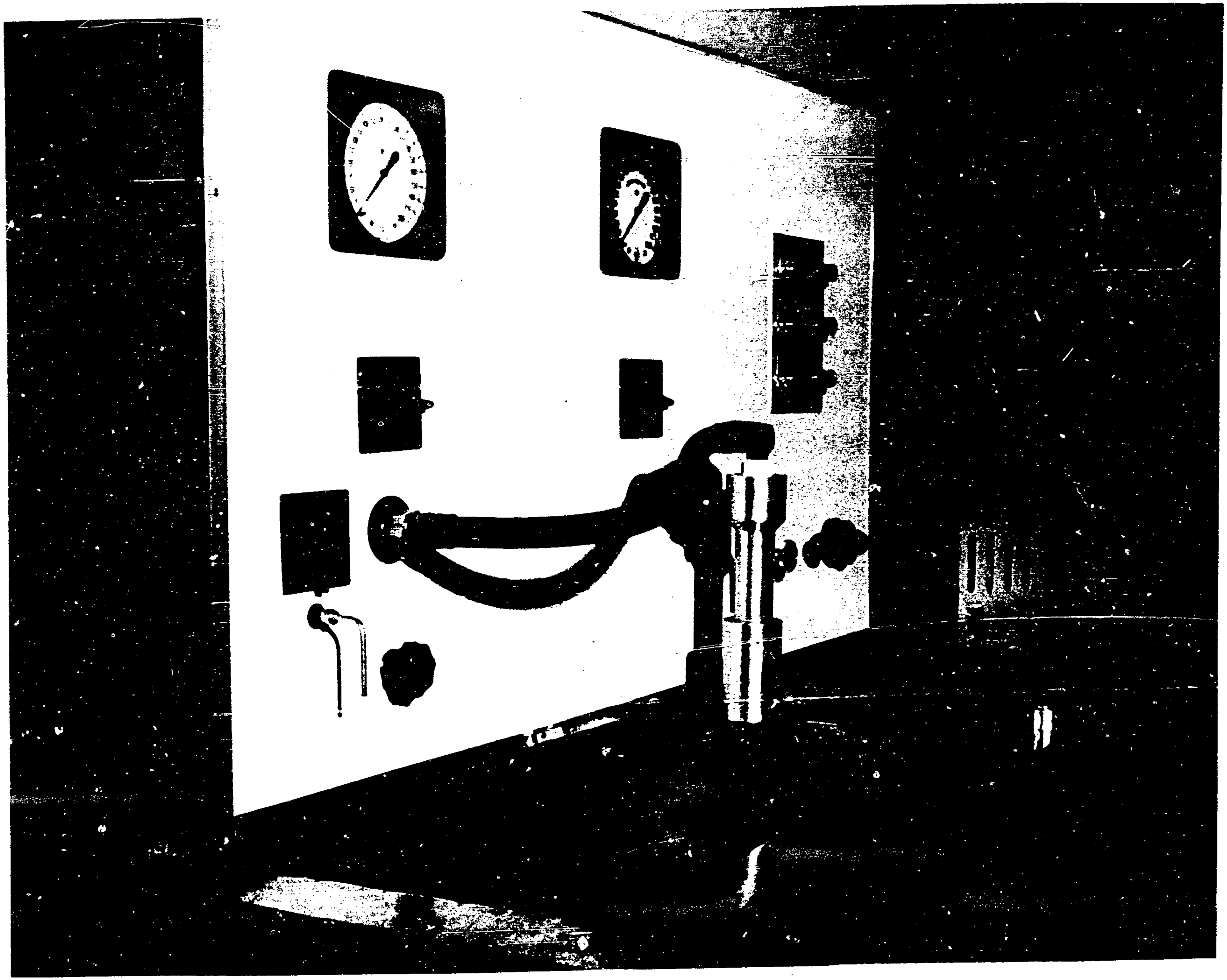

Fig. 24. Hydraulic Power Stand for Hydroclone Development

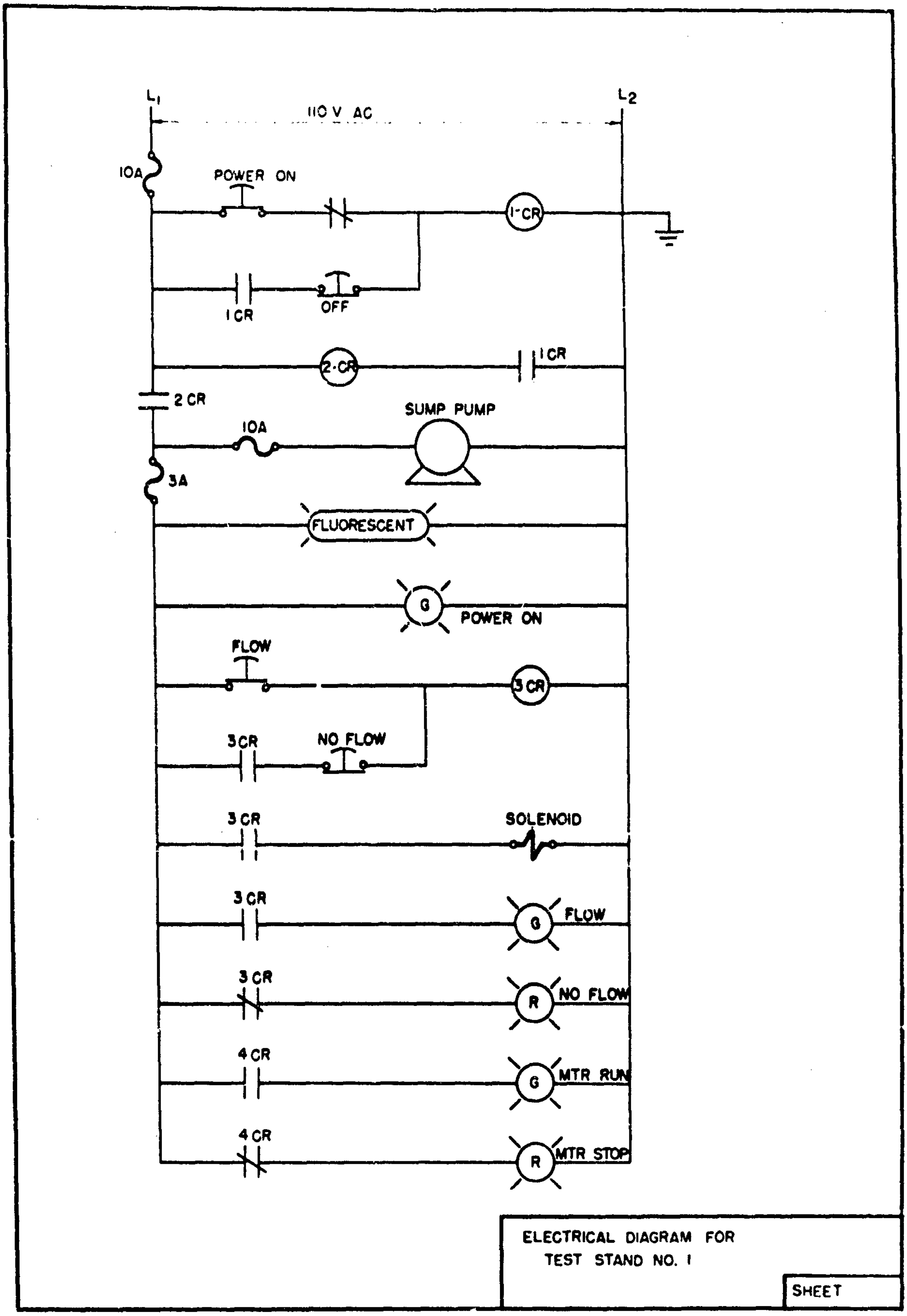

Fig. 25a. Schematic Electrical Circuit for Power Stand Control.

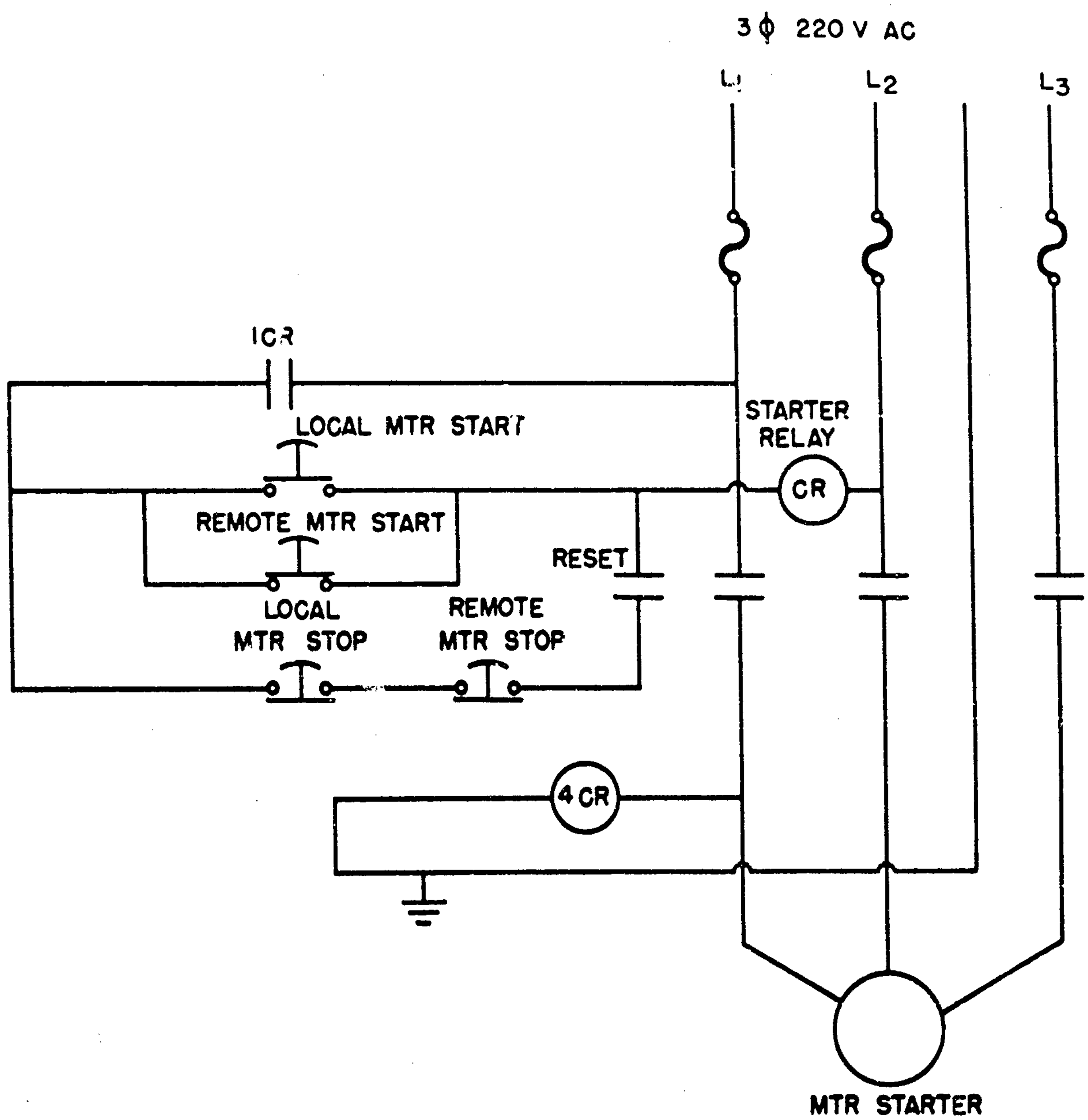

Fig. 25b. Schematic Electrical Circuit for Pump Motor Control.

momentary contact switches are mounted on the control panel. One set controls the line power, one controls the pump motor, and the third set operates the flow diversion valve. The momentary contact switches contain pilot lights to indicate the condition of each controlled component.

3. Flow Meter

The flow rate of fluid through a hydroclone has a significant effect on the hydroclone's performance. The flow meter incorporated in each hydroclone test system digitally displays the fluid flow rate in the power stand test section and enables the operator to adjust the flow control valve to a specified level. This unit contains a fixed displacement hydraulic motor with a gear mounted on its shaft. A magnetic pickup (F_1) generates a pulse every time a gear tooth passes it. These pulses are amplified (F_2) and transmitted through a gating circuit of an electronic pulse counter (N_1), and the cumulative pulses are displayed by the counter. The flow meter was calibrated against a precision turbine meter in April 1963. A diagram of the flow meter is shown in Fig. 26.

4. Contaminant Evaluation Stand

The HIAC Automatic Particle Counter (C_1, C_2) was chosen for a number of reasons. First, the operation of the HIAC is extremely simple and easily mastered. Second, the HIAC is very well suited to the techniques of laboratory analysis. Third, this counter is considerably faster than optical methods. Fourth, the counter is completely subjective; it is free from operator bias. And fifth, the HIAC performs particle discrimination by use of a photoelectric cell, thus eliminating the need for mixing the sample with other fluid having questionable contaminant levels and interactive effects. A picture of the HIAC Particle Counter stand is shown in Fig. 27.

During the operation of the inline HIAC Particle Counter, the fluid specimen is forced through a sampling tube into a fluid passage by the pressure in the main system. This fluid passage is designed so that any foreign particles in the fluid must pass single file by a counting window. A parallel light beam is focused to penetrate this window and the fluid, and finally impinges on a phototube inside the unit. The resulting phototube output is constant unless a particle passes the window and interrupts a portion of the light beam. Any interruption causes a change in the output signal by an amount proportional to the size of the particle.

The output signal is directed to a chopper section where it is either sensed or rejected, depending upon whether its amplitude exceeds the value for which the sensitivity adjustment has been set. The signals sensed by the chopper section are amplified to operate a trigger, which provides the proper pulse to operate an electronic counter.

The particle counters are operated to report contamination counts during a hydroclone test. This is accomplished by diverting a fraction

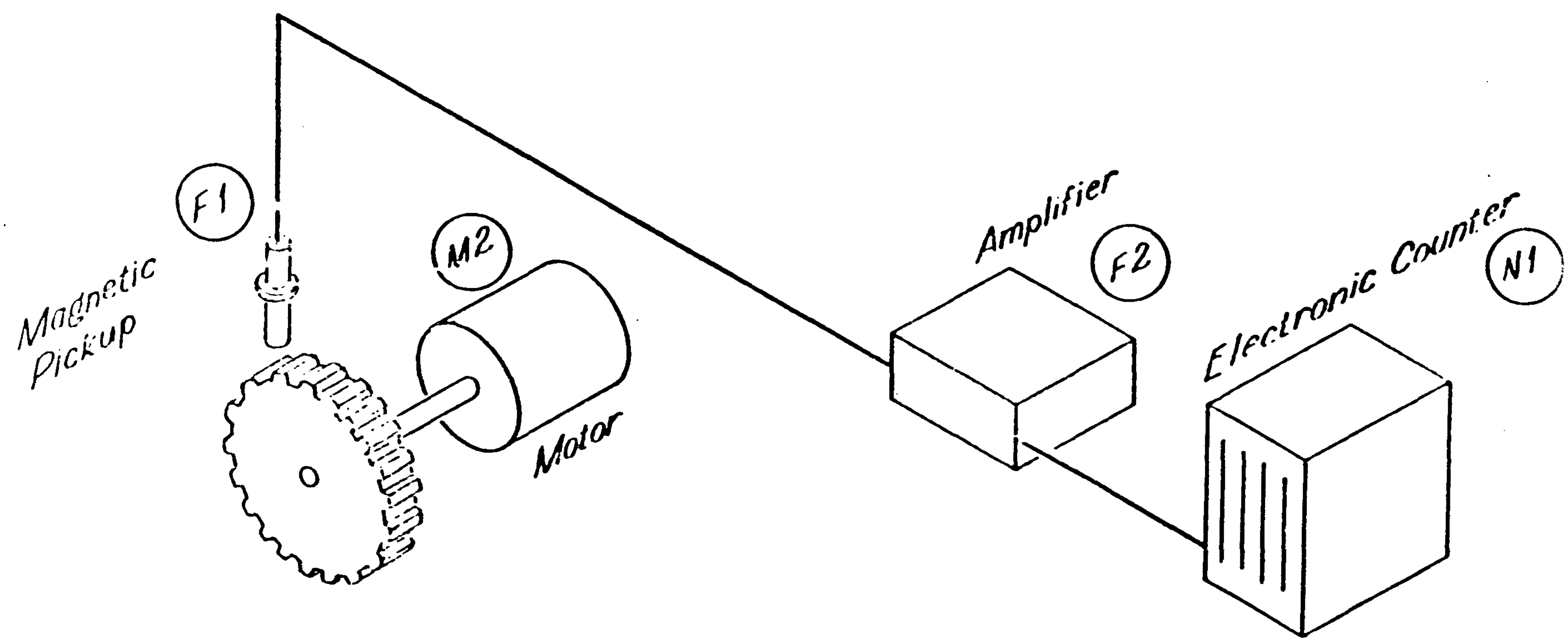

Fig. 26. **Diagram of Flow Meter System.**

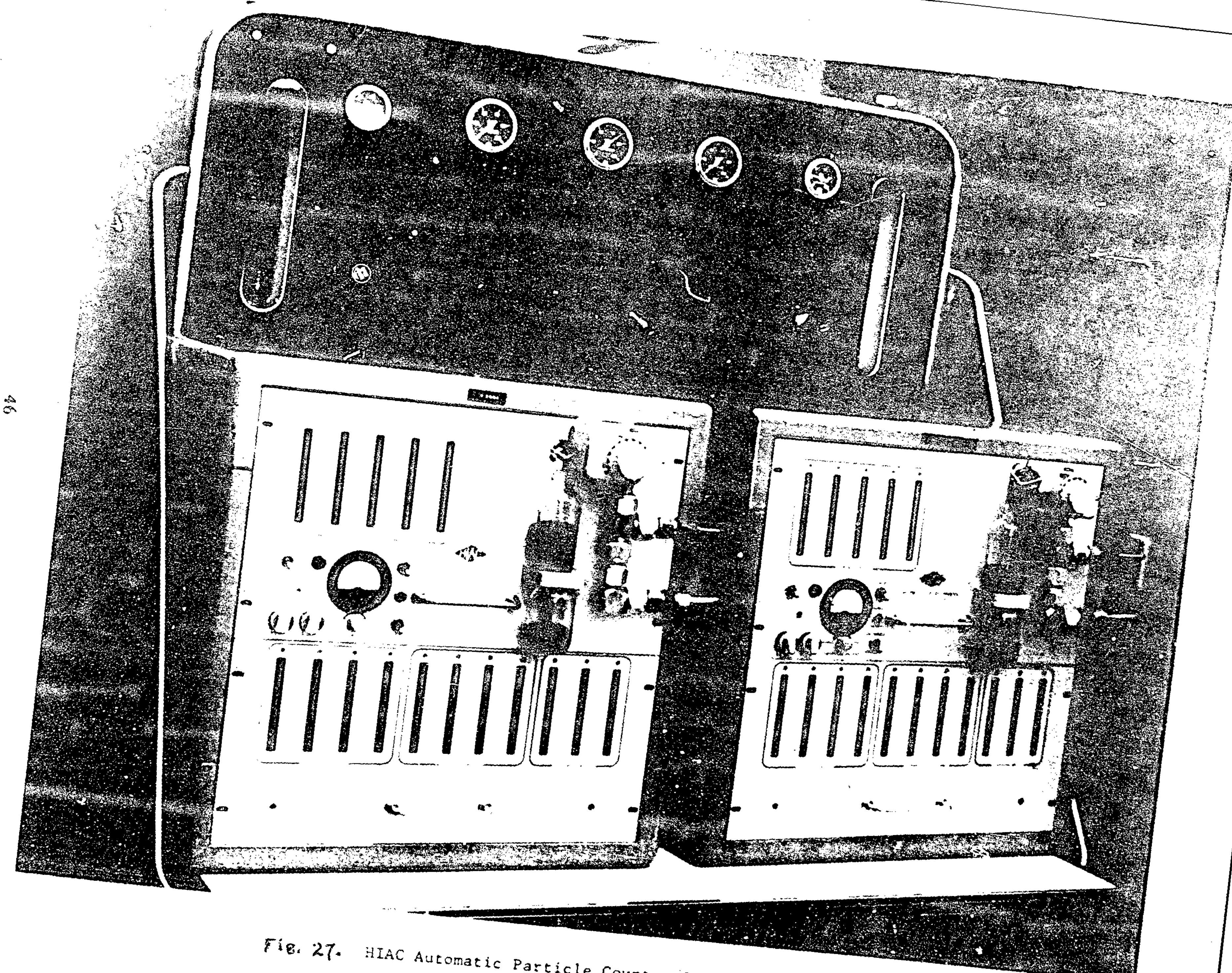

Fig. 27. HIAC Automatic Particle Counter Stand

of fluid upstream and downstream of the test unit through the two counters. The test fluid flows through adapters attached to the respective counters. These adapters cause the fluid velocity to change both in magnitude and direction, thereby creating turbulence which maintains a representative sample. From this adapter a small sample stream of 60 to 100 drops per minute is passed through the particle counter and is the quantity of fluid actually analyzed for contamination.

The flow rate of 60 to 100 drops per minute through the counter is necessary to hold the calibration constant. The fluid passage within the counter has no variable restriction, therefore, the only means of controlling this flow is by holding the pressure in the mixing chamber constant. The controlling elements are valves -- (V_4) in the upstream counter flow circuit, and (V_5) in the other counter circuit. Note also the flow meters (FM_1, FM_2) in Fig. 28. These meters are mounted above the counters and are used to indicate if the flow rate is high enough to maintain a suitable degree of turbulence in the instream adapters and if a sample of the main fluid stream is being diverted. Bypass valves (V_6, V_7) are opened to release pressure on the adapter should the pressure become too high.

An air supply piped into the stand is used to clean out the counter should it ever become plugged and also to impose a pressure head on sample bottles when this method of sampling is being used. The pressure head is necessary to displace fluid from the sample bottle through the counters.

The counter's stand is 43 inches wide and 73 inches high. The latter measurement includes the cart which forms the supporting structure for the remainder of the stand. The aforementioned flow meters and valves are mounted on a control panel located above and behind the counters. The panel serves as a mounting for five valves in addition to those already mentioned in connection with the hydraulic circuit. These five valves are used to direct air under pressure, wherever it is needed. One of these valves is a pressure regulating valve used to adjust downstream air pressure. The other four valves are ball type "ON" - "OFF" valves.

5. Injection Stand

The injection stand is used to inject contaminant into the hydraulic test system at a controlled rate. The contaminant used for the hydroclone tests is Standardized AC Fine Test Dust. The distribution of particle sizes in this test dust is shown below.

Size (Microns)	Percentage by Weight	
0- 5	39	2%
5-10	13	3%
10-20	16	3%
20-40	18	3%
40-80	9	3%

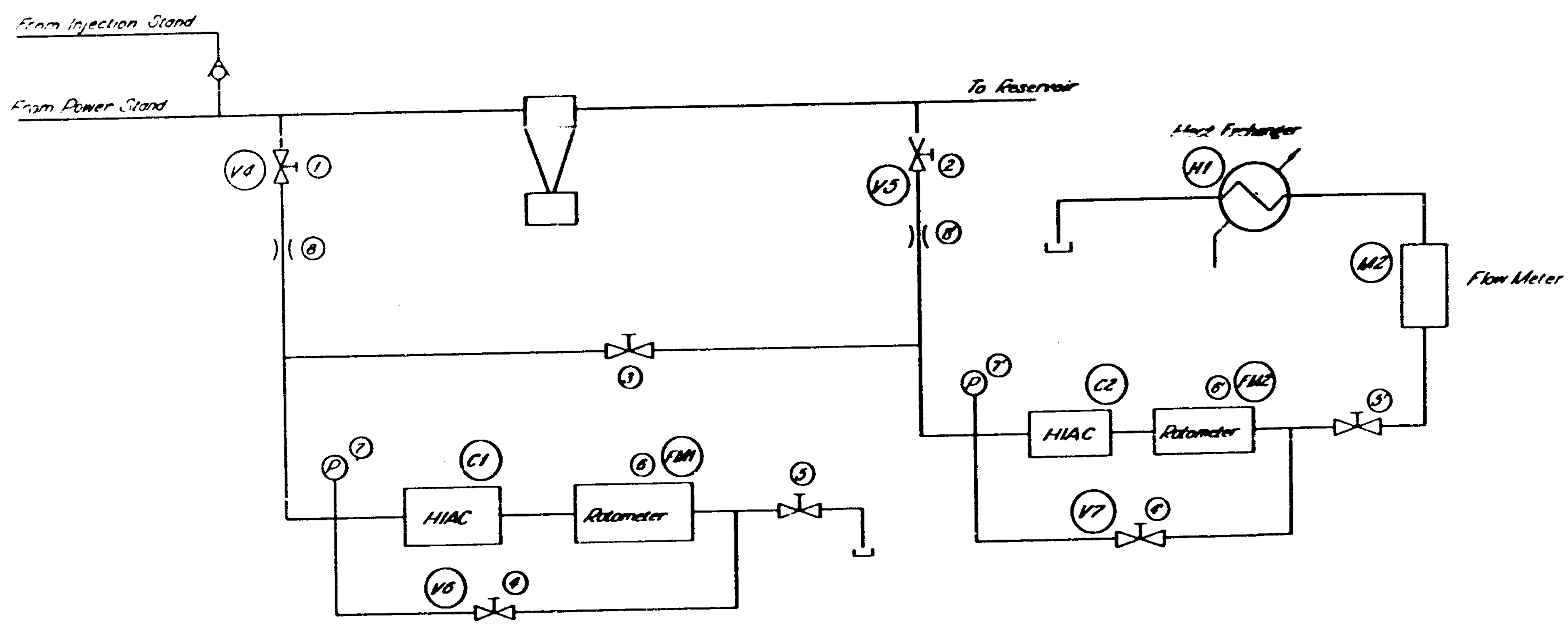

Fig. 28. Schematic Piping **Diagram of HIAC Automatic Particle Counter Stand.**

The particles to be injected are mixed with hydraulic oil, of the same type used in the test stand hydraulic system to form a thin slurry. Mixing is accomplished in a small reservoir (R_2) which is equipped with a motor driven agitator. The uniformly distributed slurry is injected continuously into the test unit section of the power stand while contamination separation data are being taken.

Fig. 23 also shows the piping diagram for the injection stand. Solenoid valves (V_9, V_{10}) in de-energized positions allow flow through the injection pump (P_2), through the power stand reservoir, and back to the injection pump. Prior to the injection of contaminant from the injection stand reservoir, the injection pump is energized, thus fluid from both pumps flows through the test section, and the flow meter reading is a report of the total flow. As soon as steady flow conditions are attained, solenoid valve (V_9) is energized and the source of fluid for the injection pump becomes the injection stand reservoir containing the previously described slurry. This change of source does not change any parameter that affects the discharge of this pump, therefore, its contribution to the total flow through the hydroclone does not change the flow conditions; and steady flow conditions prevail during the change from one reservoir to the other.

The injection pump is a gear pump of the same general type used in the power test stands. This pump will normally pump about 50 gallons of slurry before it fails due to the abrasive action of the contamination particles. Since the constant delivery characteristic is vital to the test program, the pump is periodically replaced. The maximum capacity of the pump is approximately one gallon per minute, but its delivery can be varied by changing the pump speed with a variable speed drive (D_1). This injection system provides a method of adjusting the contamination level from test to test. The injection pump speed is never changed during a test.

6. Temperature Controller

Fluid temperature is maintained within 1°F of a set point with a Minneapolis-Honeywell 3-Mode Automatic Temperature Controller (T_2). Fig. 29 illustrates the controller's circular indicating scale and adjustment knobs. The final control element of this system is a motorized water valve which regulates water flow to a heat exchanger connected in the hydraulic circuit of the power stands. The controlling device was calibrated by the manufacturer, and its performance was checked at the time of its installation approximately 1 June 1963.

C. PRESSURE DROP TEST FACILIT

In order to determine the optimum criteria for hydroclone design, a comprehensive study of the pressure drop in a hydroclone has been conducted because of the basic relationship between pressure drop and hydroclone efficiency. To perform such a study, a Pressure Measurement Test Stand was constructed that permitted the determination of

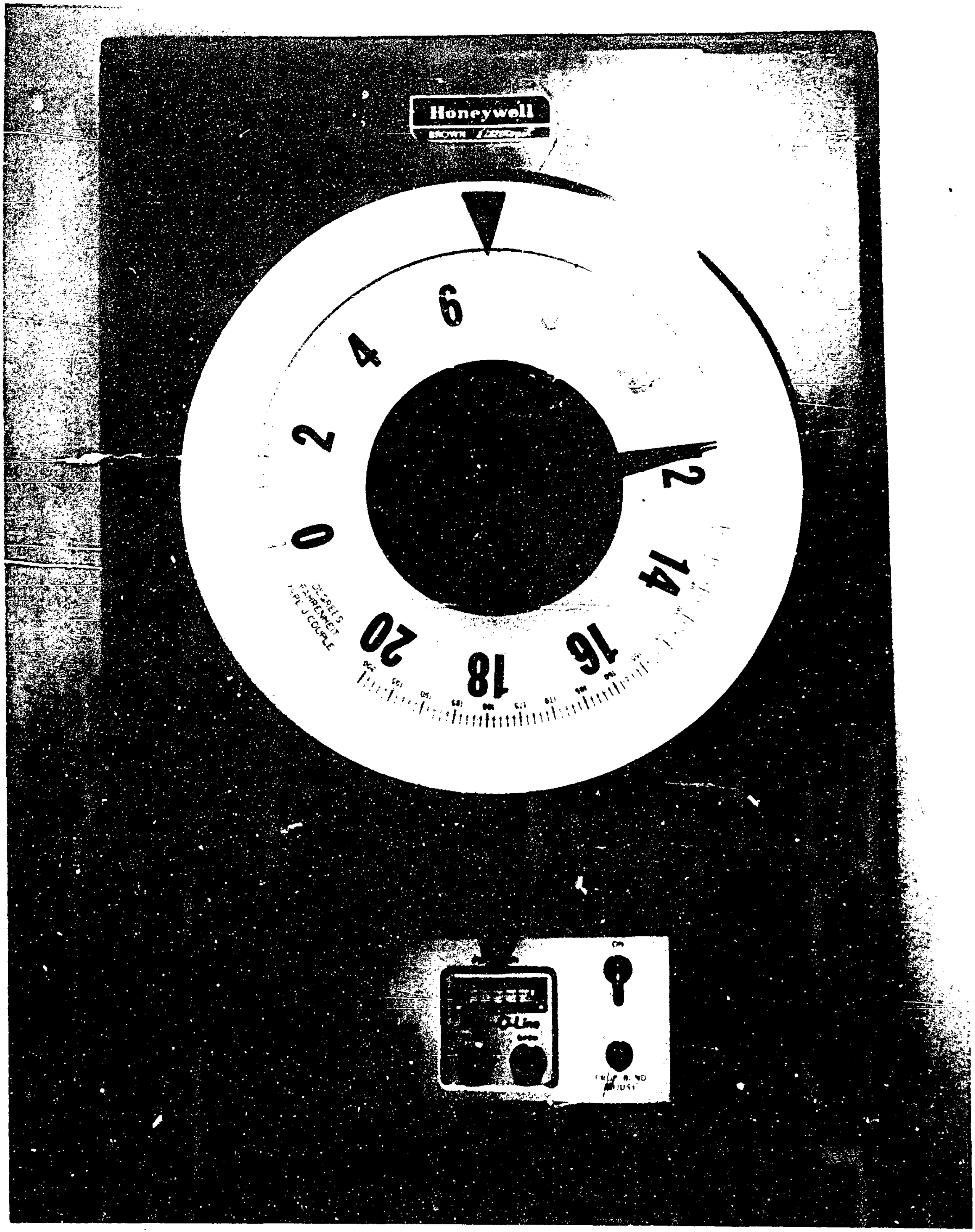

Fig. 29. Minneapolis-Honeywell Temperature Controller

the pressure differentials existing in a hydroclone. The basic stand built for the pressure drop tests consists of three sections:

(a) Power Section
(b) Test Section
(c) Pressure Measurement Section

1. Power Section

The power section of the Pressure Measurement Stand includes the controls for all essential equipment supplying power to the test stand. The power section of the Pressure Measurement Stand is identical with the corresponding power section of the Efficiency Test Stand except for the electric motor that drives the pump and the fluid reservoir. A 50 horsepower Allis Chalmers electric motor is used for driving the pump rather than a 40 horsepower motor. The pump is connected to the motor by a magnetic clutch (A_1) which has a transmission rating of 50 horsepower.

2. Test Section

The test section of the Pressure Drop Stand contains all controls for the basic power stand. A sink is located below the sample valves which allows fluid to be flushed from the lines for several minutes before a sample is taken. This insures that all particles trapped in the valves will be flushed out of the lines. The Pressure Drop Stand is also applicable to the conduction of efficiency tests. Outlets are provided for inline samples should the stand be used for efficiency tests. A provision is also made for the injection of contaminant. A more detailed explanation of the test section has been given previously.

3. Pressure Measurement Section

The Pressure Measurement Stand required precision pressure measuring equipment to detect small changes in pressure drop when a small variation in a parameter is made. In previous hydroclone tests, pressure measurements were made using a precision bourdon tube pressure gage. By connecting this gage to individual taps on the hydroclone test stand, the gage pressure of these points could be measured. Pressure differentials were calculated from the pressure readings observed at the points of concern. Each time a measurement from a different point was required, a relocation of the gage connection was necessary. Obviously, this procedure was tedious and time consuming, in addition to being inaccurate when differential pressures were calculated from readings that were not taken simultaneously.

In order to facilitate the pressure measuring requirements of the hydroclone study, a pressure measurement stand was designed and constructed. The features of this pressure stand are

(a) Direct measurement of pressure, differential or gage, by simple valve manipulations.

(b) Eight pressure line connections are provided on the top side of the control panel to facilitate measurement of the various pressures which may be pertinent in a particular test arrangement.
(c) The voltage, related to the pressure, can be read from the digital voltmeter (J_1) eliminating any reading error.
(d) The pressure measurement is divided into two pressure ranges, high pressure ranging from 0-2000 psid and low pressure, ranging from 0-100 psid. Therefore, a better resolution is provided for both high and low pressure.
(e) This portable stand is applicable to any of the hydroclone test stands in the OSU laboratory.
(f) Electronic pressure transducers (E_1, E_2) enhance the accuracy of pressure measurements.
(g) A precision bourdon (Heise) gage (G_3) (range: 0-2000 psig) which can be used for an additional pressure measurement and as a quick transducer calibration check.

4. Construction and Operation of Pressure Measurement Stand

The framework for the Pressure Measurement Stand was erected by covering the sides of a 1-inch angle iron frame with steel panels while the front and work deck have a laminated plastic surface. Fig. 30 illustrates the external features of the pressure stand.

Enclosed in the upper part of the pressure stand is a 16-inch dial, Heise, 0-2000 psig pressure gage. Twelve hand-operated valves on the control panel, located below the Heise gage, permit the selection of the pressure source from any one of eight pressure taps and permit a choice of either a high or low pressure transducer. Behind the control panel, the two pressure transducers are mounted and connected to appropriate valves.

To simplify the pressure measurement connection to the pressure source, eight pressure taps protrude from the top of the control panel cabinet. The pressure taps are divided into two groups: one group is connected to the high-pressure manifold, and the other groups is connected to the low-pressure manifold. Since both the pressure gage and the transducers are connected across the high- and low-pressure manifolds, the pressure can be measured by opening the appropriate valve. The major components of the pressure stand are listed below:
(a) The Heise Precision Gage, ranging from 0-2000 psig.
(b) A DC digital voltmeter of Cubic Model V-46-AP, made by the Cubic Corporation.
(c) Two Pace Transducers, Model P21D (1-100 psid) and Model P3D (0-2000 psid).
(d) A Pace Demodulator (U_1) Model CD-10.

Fig. 31 is a diagram of the pressure test stand. Eight pressure taps comprise the pressure inlets of the Pressure Measurement Stand. Lines from external sources can be connected to these inlet taps. Four valves connect the lines to the high pressure manifold while four

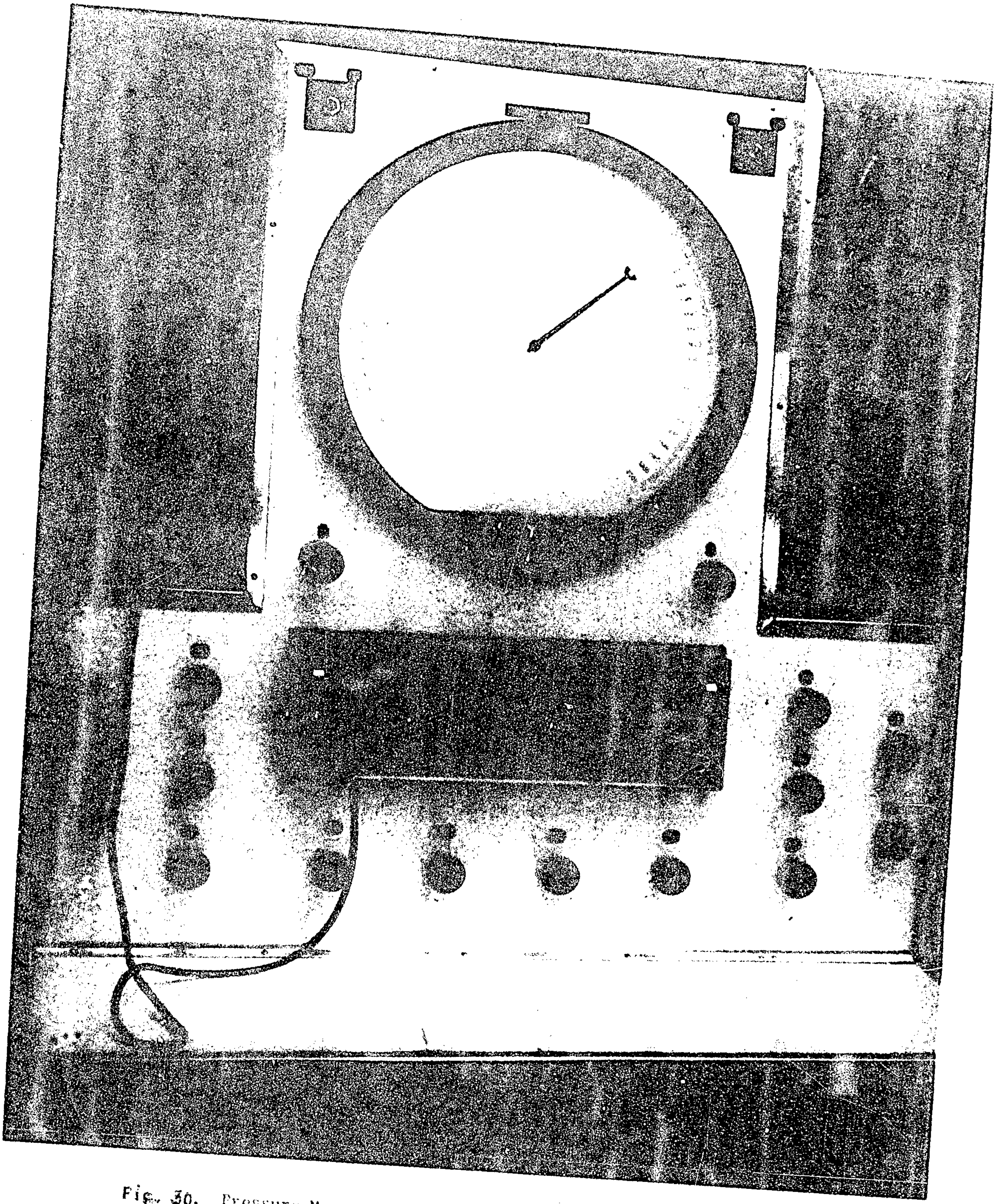

Fig. 30. Pressure Measurement Stand

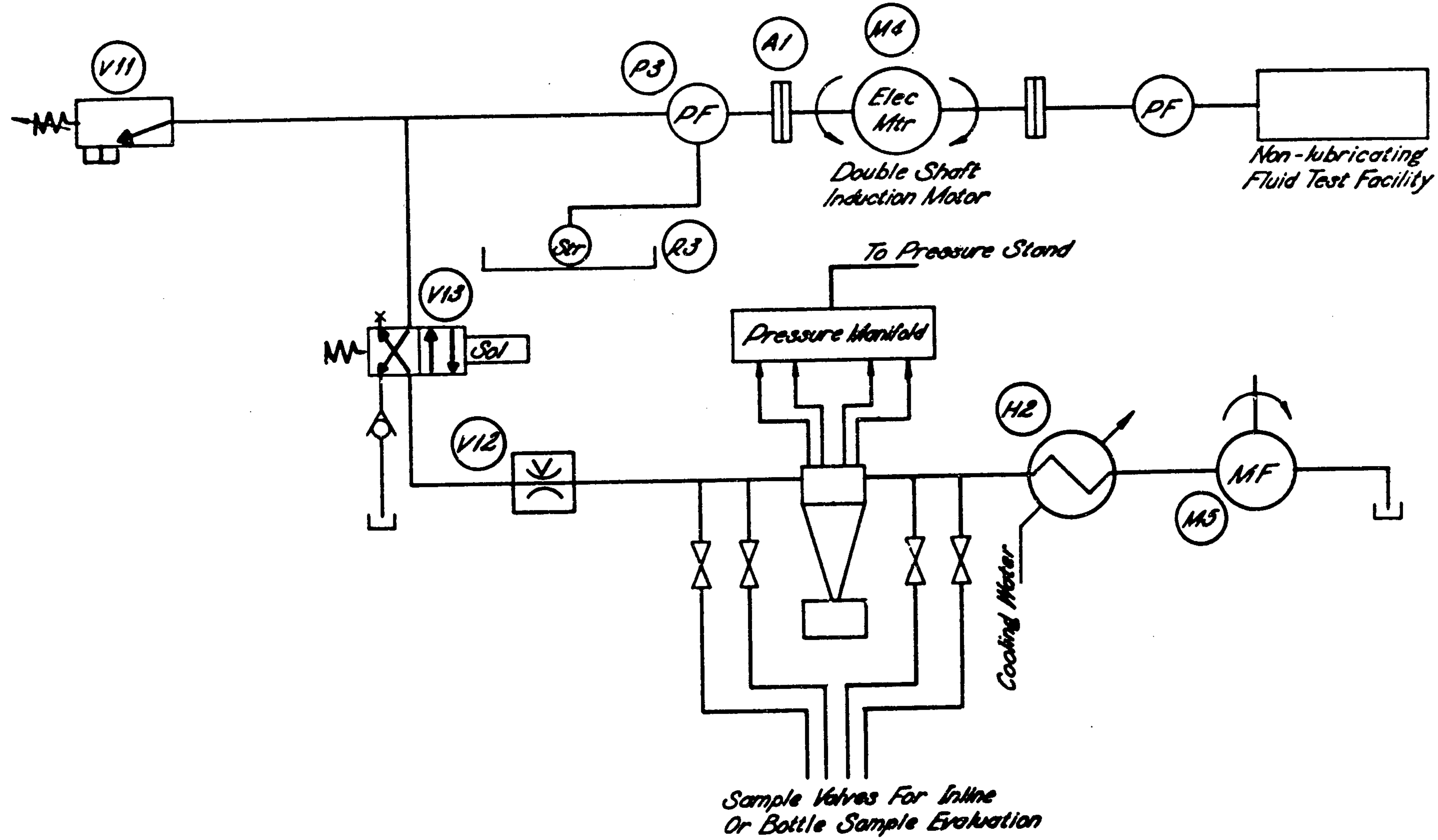

Fig. 31. Schematic Diagram of Pressure Test Stand.

other valves allow attachment of these lines to the low-pressure manifold. The Heise gage is connected to both the high- and low-pressure manifolds permitting a pressure reading of either the high- or low-pressure side, depending on the inlet selection. The Heise gage can be used as a calibration standard for approximate calibration of the pressure transducers, without depending on a dead weight tester.

There are two pressure transducers connected to the pressure lines: one is for the high differential pressure, 0-2000 psid, and the other is for the low differential pressure ranging from 0-100 psid. The pressure measurement stand utilizes these two variable reluctance pressure transducers as sensing elements. The sensing element is a flat diaphragm whose deflection varies in proportion to the pressure differential across the diaphragm. The range selector switch on the Heise gage mounting panel operates a relay which connects the selected transducer to the demodulator. The transducers with their associated solid state regulator-oscillator-demodulator circuitry convert the pressure into a relatively high level DC voltage output. This voltage output is received by the digital voltmeter from which the readings are observed. This voltage can be converted to the corresponding pressure by utilizing a voltage-pressure calibration chart.

Since the characteristics of the pressure transducer are essentially linear, two points of calibration are sufficient to obtain satisfactory results. Therefore, the calibration can be accomplished by synchronizing the zero pressure differential and maximum pressure differential across the transducer with the related readings on the voltmeter.

D. NON-LUBRICATING FLUID TEST FACILITIES

The power stand for the testing of non-lubricating type fluids was designed to facilitate the testing of fluids other than hydraulic fluid (MIL-F-5606). Such a stand was required to complete the evaluation and study of hydroclone configurations, fluids, pressures, flow, temperatures, and other pertinent parameters as stated in Section III.

The purpose of this stand is to check the efficiency and the pressure drop of an optimum-design hydroclone to further verify analytical expressions developed at Oklahoma State University. The verification of analytical expressions requires that tests be conducted on fluids other than hydraulic oil -- such as water and cleaning solvent. Therefore, it is necessary that a system be constructed of components compatible with these fluids.

1. Construction

The power stand for the non-lubricating fluid tests was constructed to minimize the number of components because of the strict limitations placed on these components.

The power unit consists of a 50 horsepower Allis Chalmers induction motor (M_4) and a Cessna Model H gear pump (P_4). The pump housing is of aluminum, and the gears are chrome plated to prevent rust or corrosion by the fluids. A special lubricant, molybdenum disulfide, is required for the pump bearings since water is to be used as one of the fluids in the test system. A magnetic clutch (A_2) manufactured by the Warner Electric Brake and Clutch Co., Model SF 1225, is used to couple the motor and pump. The system contains a relief valve (V_8) manufactured by the Texsteam Company, Type 60S, and is pre-set at 2000 psi for system protection. A bypass valve is used to govern flow rate, and a venturi meter (FM_3) is used to check flow rate. A stainless steel cylindrical vessel with spherical ends comprises the reservoir (R_4) with return lines located below the fluid level to prevent aeration of the reservoir fluid. A heat exchanger manufactured by the Young Radiator Company (H_3), Model No. 67219 is located downstream of the hydroclone, and temperature is controlled in the system by a manually operated water valve. Sample valves are included upstream and downstream of the hydroclone for efficiency tests. Pressure taps are located on the hydroclone housing to determine pressure drops across the inlet orifice, vortex core, and the overflow orifice.

Referring to the schematic diagram in Fig. 32, fluid from the pumps is partially bypassed by a manually controlled valve to maintain the correct flow rate to the hydroclone. A relief valve (V_8) downstream from the pump, protects the pump against high pressure due to accidental restriction of the flow. Downstream from the hydroclone, the fluid passes through a venturi type flow meter (FM_3). Fluid is then directed through a heat exchanger (H_3) before returning to the reservoir (R_4).

E. Test Hydroclone Design

Special hydroclone housings were built that could be disassembled and the parameters changed easily in order to test the many hydroclone configurations necessary for a comprehensive investigation. Since two power stands were constructed for efficiency and pressure drop tests, two housings were constructed so that personnel could check separation efficiency on one stand and pressure drop on the other. The two housings are proportionally designed, enabling one research group to test efficiency of large diameter hydroclones while the other group tests pressure drops of small diameter hydroclones. Since both housings have the same provisions for efficiency and pressure drop tests, the hydroclones can be interchanged to test efficiencies of small diameter hydroclones and pressure drops of large hydroclones.

With the two test hydroclone housings (1.50 inch and 1.25 inch), tests can be conducted on hydroclones with diameters ranging from 0.75 inches to 1.50 inches. The 1.25 inch housing can accommodate hydroclones as small as 0.75 inches and as large as 1.25 inches. The 1.50 inch housing is adaptable to the testing of hydroclones with a diameter range from 1.25 inches to 1.50 inches. These hydroclone housings, illustrated in Fig. 33, were designed in four sections:

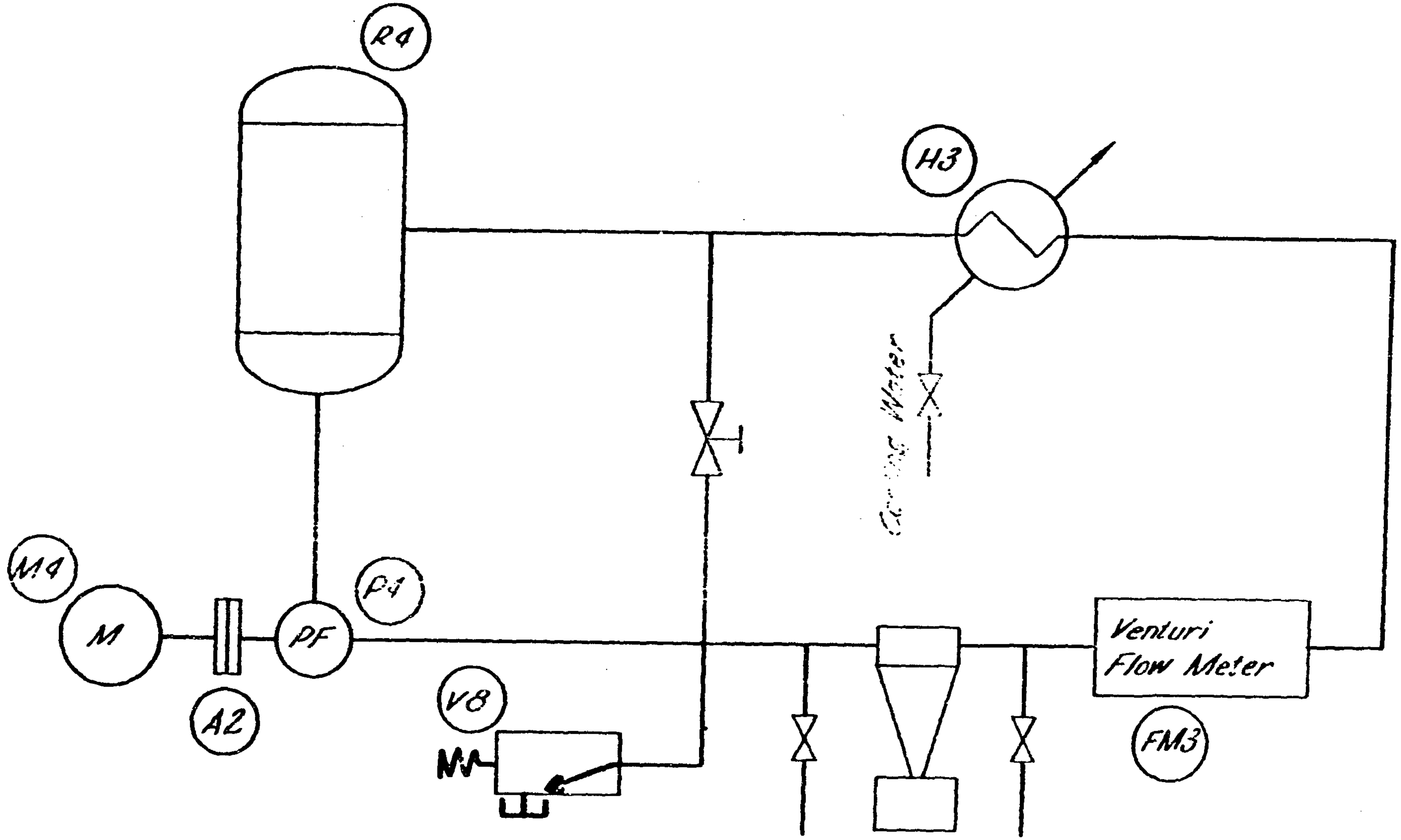

Fig. 32. Schematic Piping Diagram of Non-Lubricating Test Facility.

(a) Head or inlet ring housing
(b) Cone housing
(c) Overflow nozzle housing
(d) Collection chamber.

The head or inlet ring housing which is the main section of the test hydroclone provides the alignment for the cone and overflow nozzle housings, as shown in Fig. 33a. The cone housing is supported on a lip at the bottom of the inlet ring housing, thus providing the necessary alignment. The cone housing or sleeve holds the cone in alignment with the overflow nozzle and inlet ring. The overflow nozzle housing has nozzle inserts which can be interchanged by pressing the inserts out of the housing and replacing them with the desired insert size. The collection chamber has an adapter ring which permits the addition of a collection chamber of any size and configuration to the hydroclone, and also provides a space for a seal between the collection chamber and the cone sleeve.

The components that must be changed to investigate certain parameters are:

(a) Overflow nozzle
(b) Inlet ring
(c) Cone.

The overflow nozzles consist of aluminum inserts that are interchangeable and are pressed into the overflow nozzle housing; therefore, only one housing and several inserts are required to study the optimization of the overflow diameter by pressure drop and separation efficiency methods. The inlet rings shown in Fig. 34 consist of a circular piece of aluminum with a concentrically bored hole which is equal to the diameter of the hydroclone. Each ring has a particular nozzle configuration corresponding to the size required for a given test.

The cones used for these studies are constructed by casting a polyester resin with an aluminum powder base over an aluminum mandrel. The aluminum powder base polyester resin is much easier to machine than the raw polyester resin. The inner coating of these cones does not have aluminum powder mixed with it because the resin without the aluminum powder is much harder and wears longer. The aluminum mandrels shown in Fig. 34 have a polished surface which provides a smooth finish for the cast cone. Mandrels ranging from 1.00 inches to 1.50 inches, in increments of 0.25 inches, are available for hydroclone study. The angles of the mandrels vary from 6 degrees to 20 degrees for the 1.50 inch mandrel and from 6 to 10 degrees for other diameters of mandrels. Pressure taps are placed at the inlet, top of vortex finder near the vortex finder wall, and the overflow. These pressure taps are used to determine the pressure drop across the inlet, vortex, and overflow. A pitot tube, shown in Fig. 34, is located on a ring and suspended between the inlet ring and the cone, and is used for determining the velocity of the fluid at the inside wall of the hydroclone.

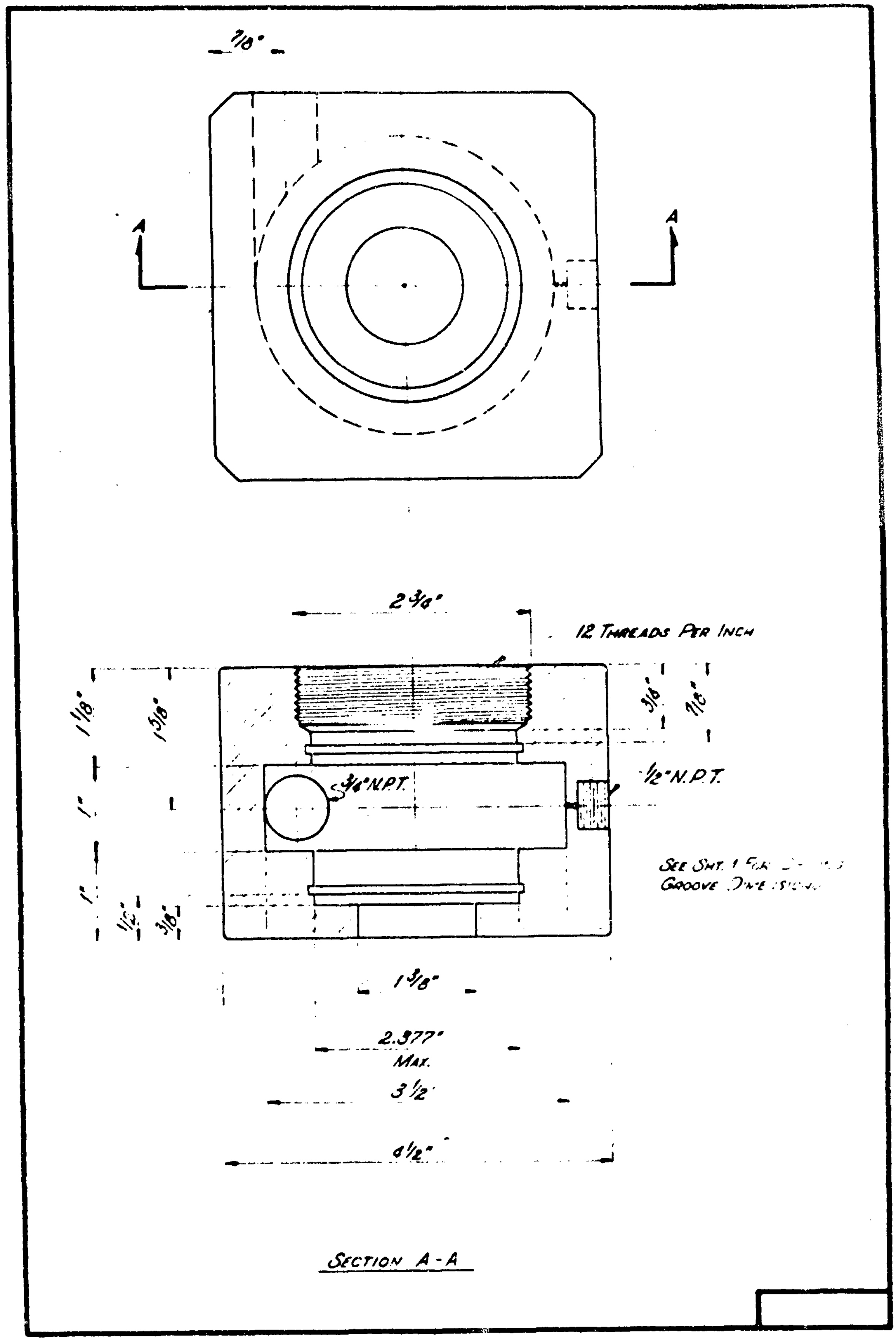

Fig. 33a. Hydroclone Housing Section.
(Inlet Ring Housing)

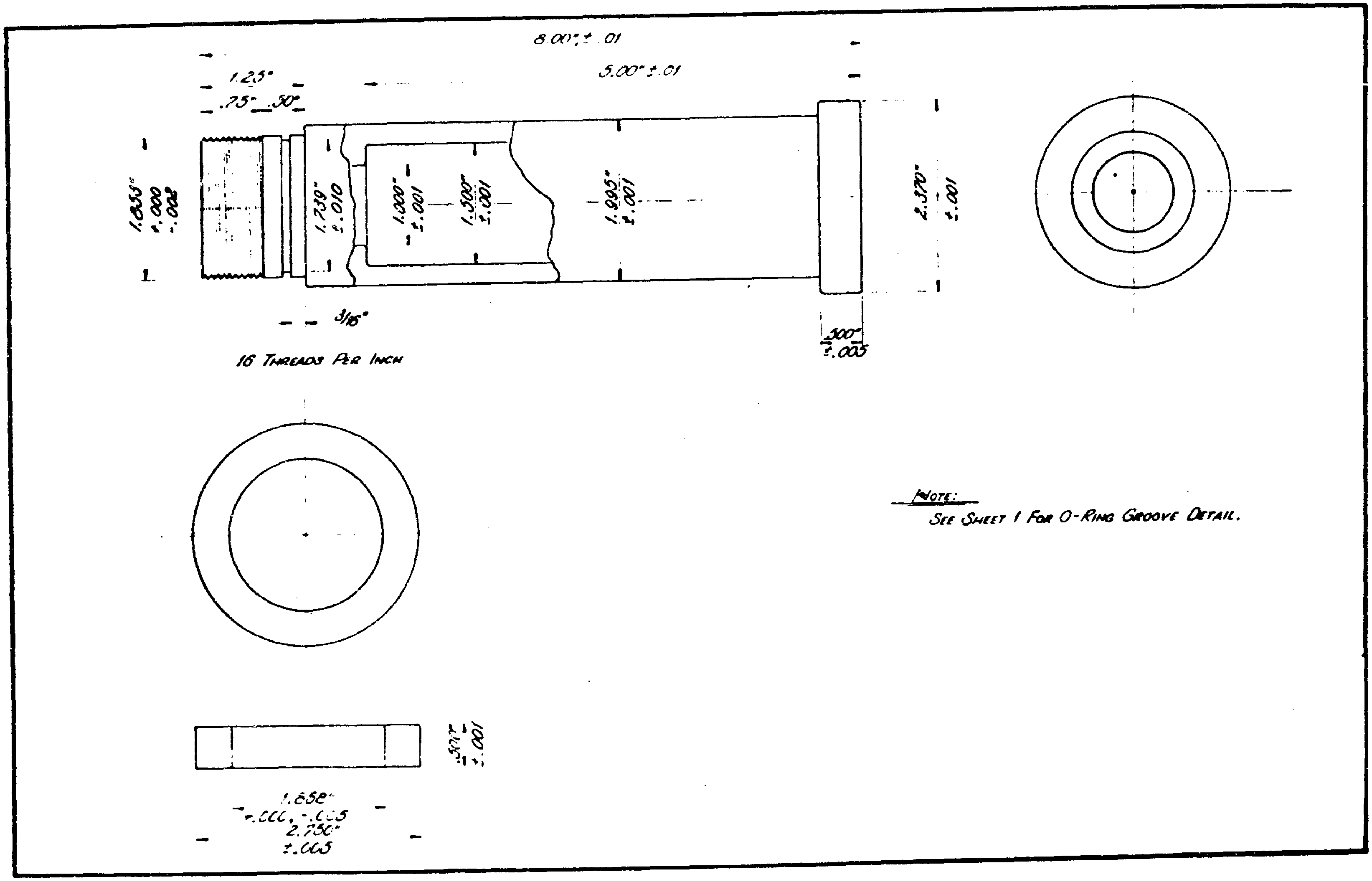

Fig. 33b. Hydroclone Housing Section.
(Cone Housing)

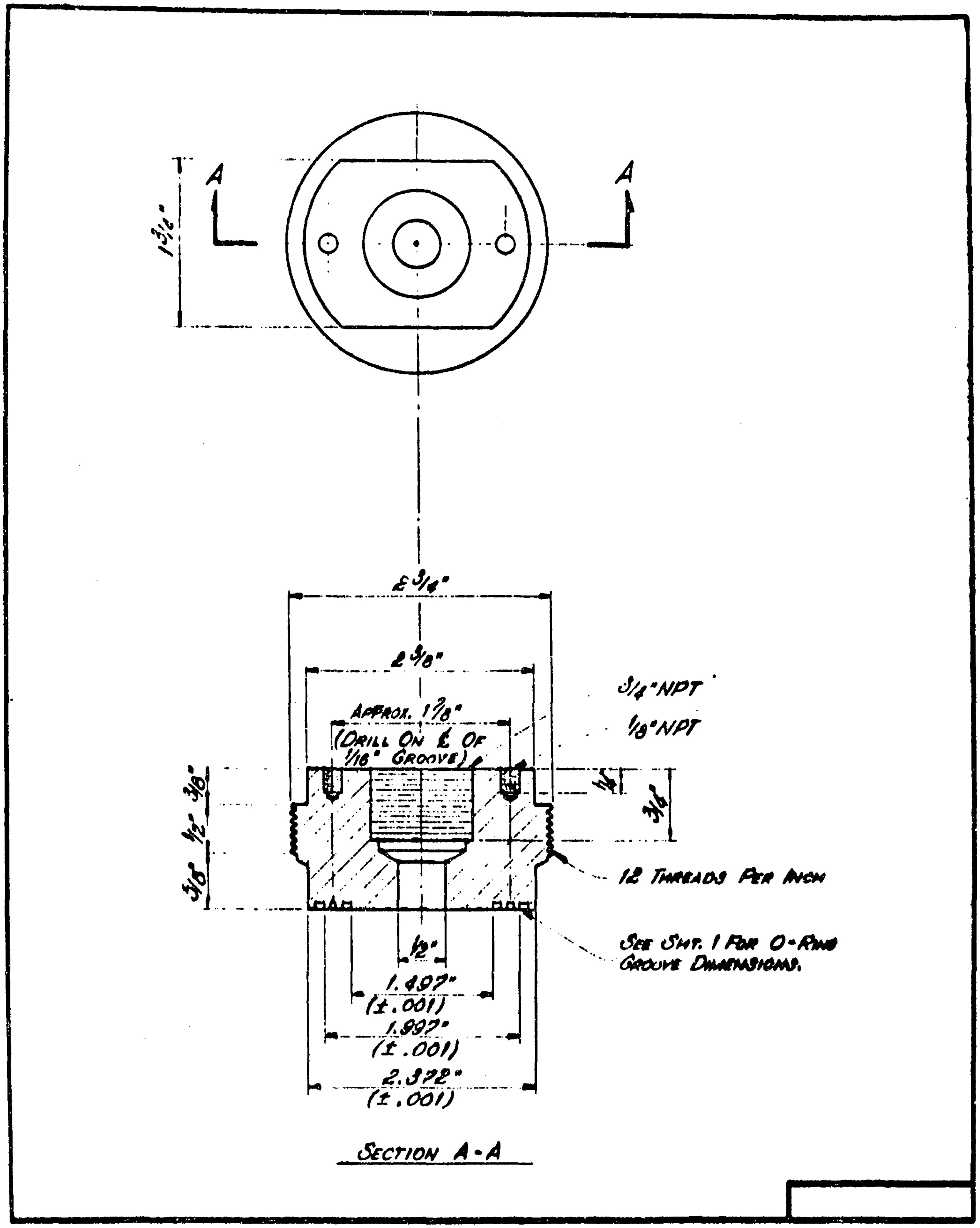

Fig. 33c. Hydroclone Housing Section.
(Overflow Nozzle Retainer)

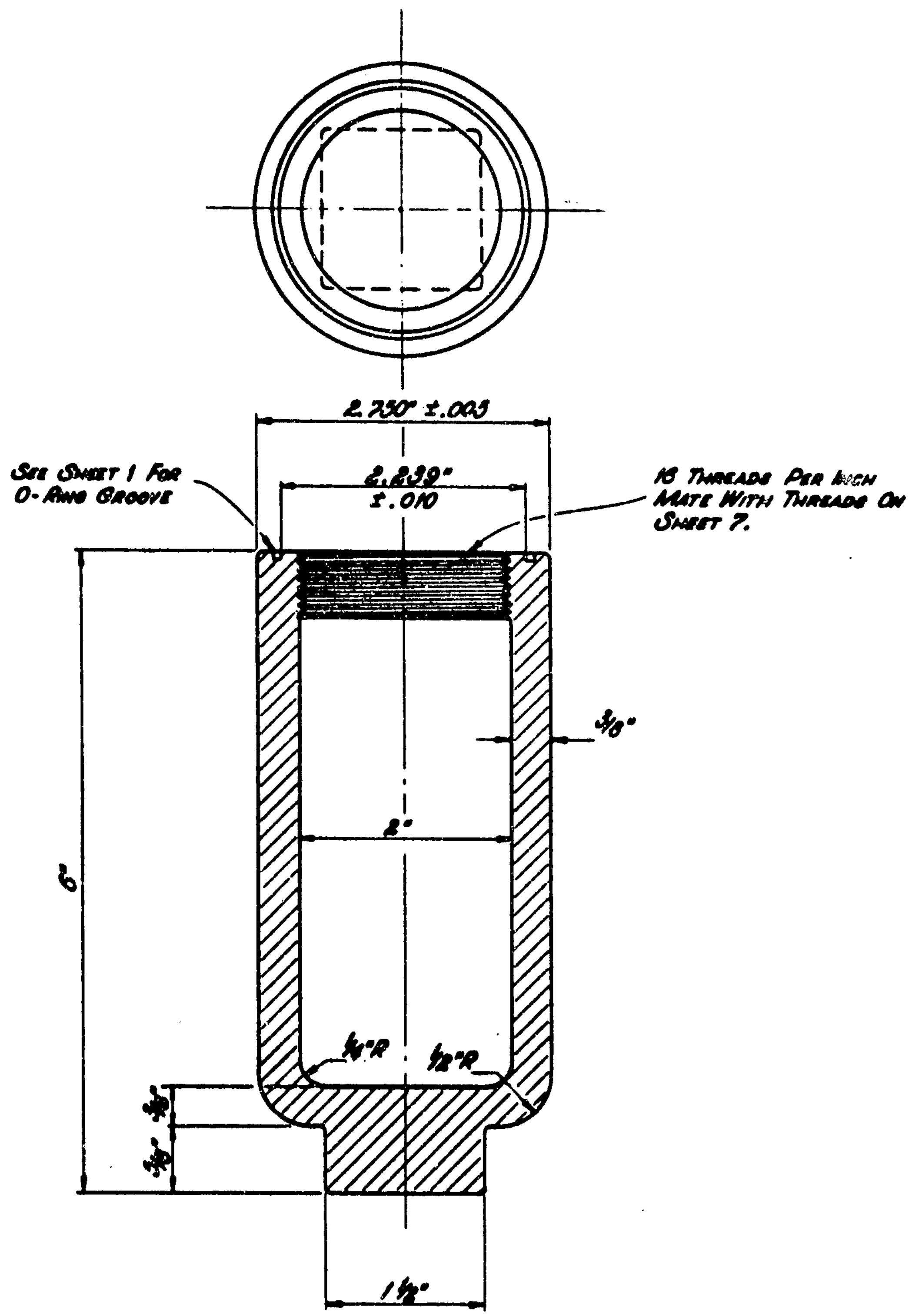

Fig. 33d. Hydroclone Housing Section.
(Collection Chamber)

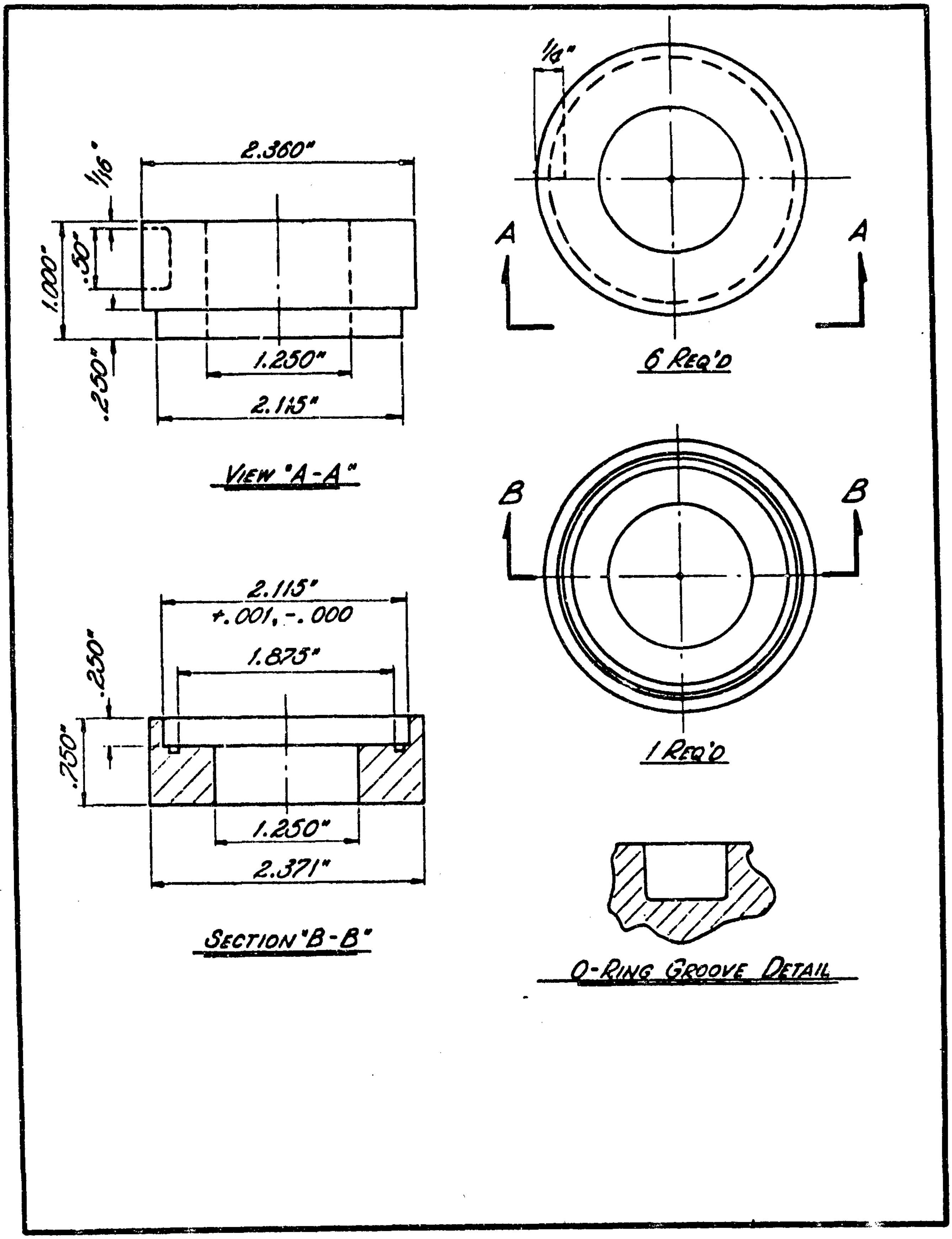

Fig. 33e. Hydroclone Housing Section.
(Inlet Ring)

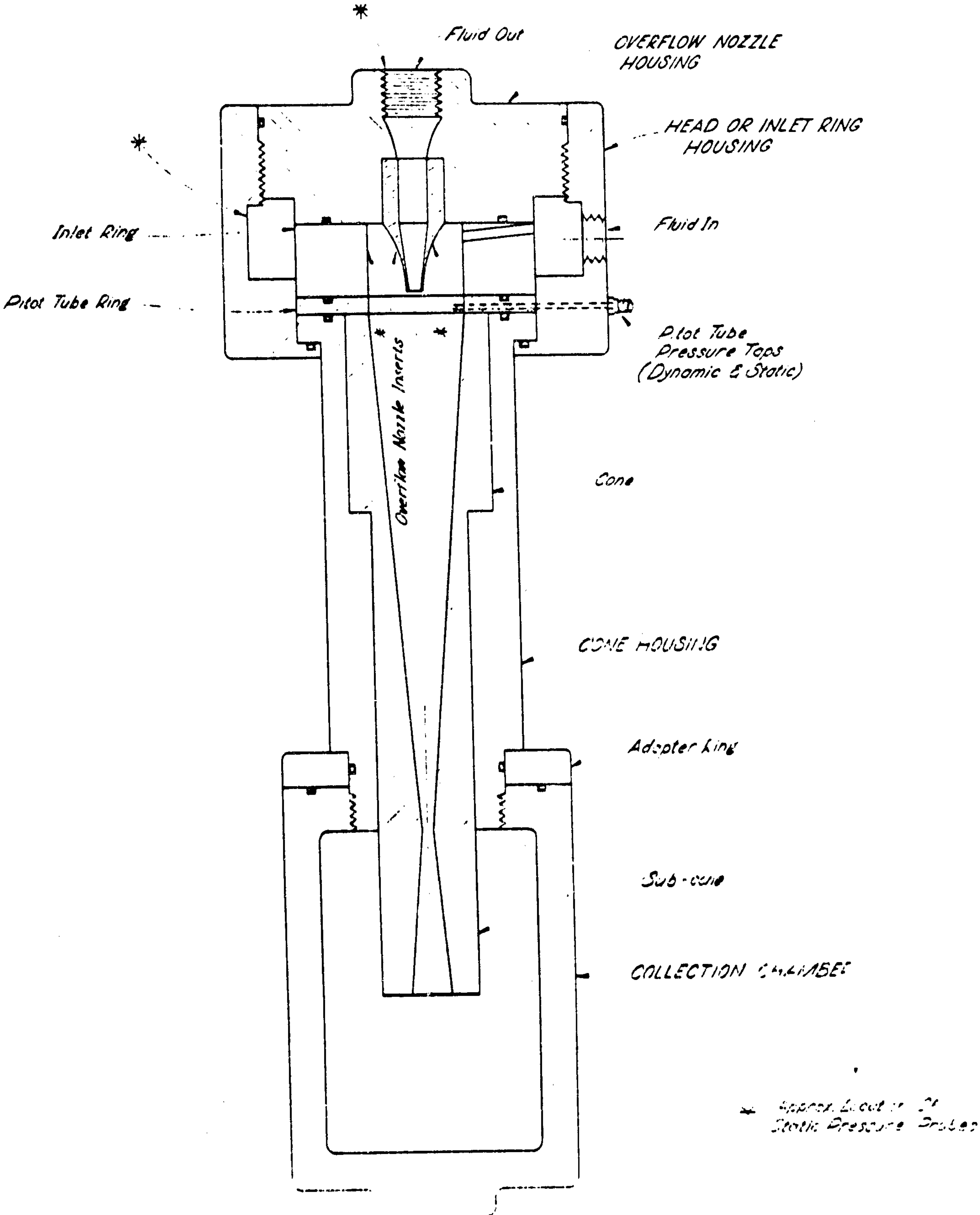

Fig. 34. Components of Hydroclone.

F. EVALUATION OF EQUIPMENT

As a result of the stringent requirements set forth for the equipment in the hydroclone research project test program, a major portion of personnel time was spent in the application of equipment to unique situations. These unique situations have inherent problems, arising when the equipment is used for an application or an environment different from that for which the equipment was originally designed. Some of these problems were easily solved, while others took considerable time to correct. In some instances, the problem could not be solved in the time given for the test program, and the problem was "lived with." A discussion of these problems, their solutions, and recommendations for future equipment to alleviate these problems are presented herein.

To simulate an activated hydraulic system, whereby the efficiency of a hydroclone can be determined, it is necessary to have some means of injecting contaminant into the test system. A proximity of the contaminant level in a veritable hydraulic system could be accomplished by the use of a constant displacement pump and a variable speed power unit volume so that the contaminant weight rate per unit volume of fluid could be of infinite control. It is realized by OSU personnel that the use of a gear pump to inject contaminant into a high pressure system is unsatisfactory from the standpoint of long-life service of the pump. This is due to the fact that most gear pumps use the oil of the test fluid to lubricate the pump bearings. However, it is also realized that it becomes necessary to use a gear pump to maintain a constant, uniform injection over a period of minutes in order to obtain accurate separation efficiency results. Other types of pumps designed specifically for high contamination concentration are not feasible because of their large size (resulting in stagnant or dormant areas) and pressure limitations. Therefore, a relatively inexpensive gear pump was purchased and used to inject contaminant until the pump became ineffectual, at which time the pump was replaced. A means of injecting clean fluid into the pump housing through the bearings was attempted to lubricate the pump bearings and consequently increase the life of the pump. However, the low pressure seal on the upstream side of the pump would not hold because of the high pressure required to force the clean oil through the bearings. Consequently, fluid leaked around the seal.

In future work, the possible modification of a gear pump by lubrication of the bearings with clean oil should be attempted again because of the successful results obtained by using a gear pump for injection purposes.

Perhaps the most difficult of the problems encountered was obtaining consistent results with the automatic particle counters. Since the counters were unable to hold their calibration over a long period of time, the photo-electric cells were returned to the manufacturer where the difficulty was corrected. Installation of a combination of check valves and restrictors were required to maintain fluid pressures to the counters below the pressure rating of the counters as the test fluid flow was varied from zero to full flow. Another problem

confronting personnel was that the two counters would not record congruent particle counts when sampling the same fluid stream, even though the counters were individually calibrated for the same size particle ranges. This inconsistency in displaying the same number on both counters was due to the extreme sensitivity of the counter circuits. The problem was solved by adjusting the sensitivity control on each counter, while sampling from the same fluid stream, until both counters displayed the same number of particles in each range.

The method and equipment for the dynamic sampling system prevented personnel from obtaining large particle counts of the large size AC Test Dust. This inability to measure a large number of particles 20 microns and greater may be caused by the location of the pickup equipment with respect to the fluid stream. Since the separation efficiency of particle sizes 20 microns and smaller was of prime concern, the lack of ability to count the sizes of particles did not prohibit the testing of the hydroclones. However, a better means for obtaining dynamic samples in future tests is needed so that an over-all sample of the fluid contaminant can also be taken.

The function of the digital voltmeter, discussed in C-3 of this section, is to detect small changes in pressure drop when a small variation in a parameter was made. However, the sensitivity of the instrument prevented its use in the pressure drop tests. Small pressure fluctuations from the pump and pressure changes due to the instability or turbulence of flow in the hydroclone were picked up by the instrument, making it impossible to acquire a correct reading. To acquire accurate readings, capillary tube dampers were installed in the measuring lines to the transducers. In low pressure tests, a precision pressure gage and manometer were used to detect these small changes. Although obtaining data using the gages and manometers was a slow process, the instruments were within the accuracy requirements of the test; and the results were satisfactory.

An explanation of the construction, calibration, and theories of operation, has been given to familiarize the reader with the equipment used to conduct the Hydroclone Research Project. Justification is included for the selection of some items of equipment where other apparently comparable equipment were available. Many items were chosen because of their excellence, while other items were chosen on a low-bid basis from a list of identical pieces of equipment.

The particle evaluation stand is considered unique in that HIAC Counters are used to monitor upstream and downstream samples of fluid continuously. Fluid circuitry and counter sensitivity control allow duplicate enumeration on the two counters when monitoring the identical fluid system.

The injection system is so designed that efficiency results can be reproduced from day to day in almost exact fashion. The contaminant concentration set by laboratory personnel remains constant over a period of time and gives excellent efficiency results.

SECTION V

HYDROCLONE PRESSURE DROP STUDY

A. INTRODUCTION

The first phase of the testing program conducted at OSU consisted of the determination of optimum hydroclone parameters from pressure drop data. These different parameters were optimized by recording the pressure drops across the different components of the hydroclone and determining the effect of these components on the efficiency of the hydroclone. The efficiencies were obtained using theoretical equations along with hydroclone pressure drop data. These tests included a complete analysis of the pressure drops existing in a hydroclone from which a study was made of hydroclone parameters, as well as other special tests designed to afford a synoptic view of a hydroclone's performance. The hydroclone parameters selected for this investigation were the inlet diameter, overflow diameter, underflow diameter, cone angle, and the hydroclone diameter.

The purpose of optimizing the hydroclone parameters by pressure drop tests was to insure that the prototype hydroclone would operate at a prescribed separation efficiency and at the same time consume the least possible hydraulic horsepower. The power consumption of a hydroclone depends on the pressure drop across three parameters, the inlet, the overflow, and the cone diameter.

Since the total pressure drop across the hydroclone is the sum of the pressure drops across the inlet, cone section, and the overflow, it is reasonable to assume that only these parameters could actually be optimized from a pressure drop study alone, and that contaminant injection tests would be needed to complete the design of the optimum hydroclone. Although this design limitation was recognized by OSU personnel prior to the pressure drop investigations, all of the parameters were pursued in an effort to actually determine the effect of each parameter on pressure drop. The data collected from these investigations revealed that two of the parameters had no significant effect on the pressure drop. These parameters were the cone angle and the diameter of the underflow. Since the pressure drop tests could not be used to study these parameters, intensive efficiency tests were conducted to determine their optimization.

B. PRESSURE DROP THEORY

Many equations have been presented in various literature to predict the pressure drop and efficiency of a hydroclone. Most of these equations are empirical and very few have been thoroughly tested experimentally. Intensive literature surveys at OSU have revealed the need for more reliable equations to predict the relationship between the various hydroclone parameters and their correlation with separation

efficiency and the pressure drop within the hydroclone.

The majority of the equations presented to predict hydroclone efficiency have incorporated what is known as a $D_{50\%}$ rating. The $D_{50\%}$ is not, in the true sense, a separation efficiency but the particle diameter that is separated with 50% efficiency.

Matschke and Dahlstrom (65) presented an equation for $D_{50\%}$. Although theirs is purely an empirical equation, they have shown that it could be used to approximate the efficiency of a miniature hydroclone. The main disadvantages of the Matschke and Dahlstrom equation are that it does not account for the fluid viscosity and does not include the diameter of the hydroclone as a function of the $D_{50\%}$ efficiency.

A revised $D_{50\%}$ equation was presented by Haas, et al (53). Although this equation was based on certain assumptions and was not developed from experimental data, it does show that $D_{50\%}$ is a function of the diameter of the hydroclone and also takes into account the effects of fluid viscosity.

Bradley (17) pursued the efficiency equation further in that he presented a $D_{50\%}$ equation in which his theoretical $D_{50\%}$ equation had been experimentally supported; but unfortunately, it was only verified for small hydroclones with extremely small flow rates (.25 to .75 gpm). Also, the $D_{50\%}$ equation presented by Bradley does not include the overflow diameter as a parameter of hydroclone efficiency. Since the overflow diameter proved to be a critical separation efficiency parameter, plus the fact that the $D_{50\%}$ equation had only been verified for smaller units, OSU personnel were forced to rely on another equation that would more nearly satisfy the flow and pressure requirements of the prototype unit and yet incorporate all of the pertinent hydroclone parameters.

Recognizing the need for improved theoretical equations to predict the pressure drop and the efficiency of a hydroclone, C. R. Gerlach (48), one of the co-inventors of the OSU hydroclone, derived the following $D_{50\%}$ equation:

$$D_{50\%} = \frac{3N\beta_e^2}{V_o}\left[\frac{\pi\mu r_c^3 \tan\varphi/2}{Q(\rho_s-\rho_L)(1-\delta)}\right]^{\frac{1}{2}} \qquad \text{Eq. 8}$$

where N = number of inlets
- β_e = effective dimensionless inlet radius
- V_o = dimensionless tangential velocity
- μ = absolute viscosity
- r_c = radius of hydroclone
- φ = cone angle
- Q = flow rate
- δ = dimensionless overflow radius
- $\rho_s-\rho_L$ = relative density.

This $D_{50\%}$ equation was much improved over Bradley's since it included the overflow diameter as a parameter of the efficiency of a hydroclone.

Eq. 8 was derived by equating the radial forces in the cyclone section of the hydroclone. The two opposing forces that directly affect particle separation are the viscous drag force (acting inward) and the centrifugal force (acting outward). These two forces can be expressed as follows:

$$F_c = \frac{\pi}{6} D^3(\rho_s - \rho_L)\frac{v_c^2}{R} \qquad \text{Eq. 9}$$

$$F_D = 3\mu\pi D V_R \qquad \text{Eq. 10}$$

where V_R = radial velocity
D = particle diameter
v_c = tangential velocity
r = radial distance in hydroclone
μ = viscosity
$\rho_s - \rho_L$ = relative density.

Equating these two forces and solving for the diameter D, Eq. 8 can be derived. The only assumption that was made in this derivation was that of using Stoke's Law as a valid approximation of viscous drag. This is a valid assumption using spherical contaminants; and since all injection tests conducted at OSU involved AC Test Dust, the comparison of any efficiency calculated with Eq. 8 with injection tests will be a valid comparison.

The total pressure drop of a hydroclone is the sum of the pressure drops across the inlet, cone section, and the overflow. This can be expressed mathematically as follows:

$$\Delta P_T = \Delta P_i + \Delta P_c + \Delta P_o \qquad \text{Eq. 11}$$

where ΔP_T = total hydroclone pressure drop
ΔP_i = pressure drop across the inlet
ΔP_c = pressure drop across the cone section
ΔP_o = pressure drop across the overflow.

These three pressure drops were derived by Gerlach and presented here separately as follows:

$$\Delta P_i = \frac{\rho_L}{2}\left[\frac{Q}{NC_{D_i}\pi\beta_r^2 r_c^2}\right]^2 \qquad \text{Eq. 12}$$

$$\Delta P_o = \frac{\rho_L}{2}\left[\frac{Q}{NC_{D_o}\pi\delta^2 r_c^2}\right]^2 \qquad \text{Eq. 13}$$

$$\Delta P_c = \frac{\rho_L Q^2}{N\pi\beta_e^2 r_c^4} \cdot C_3 \qquad \text{Eq. 14}$$

where C_{D_i} and C_{D_o} are coefficients of discharge.

Eqs. 12 and 13 can basically be derived by considering the inlets and the overflows to be nozzles with coefficients of discharge, while Eq. 13 is a more rigorous derivation from Euler's equation of flow (48).

Combining Eqs. 12, 13, and 14, the complete pressure drop across the hydroclone can be expressed as follows:

$$\Delta P_t = \frac{\rho_L Q^2}{2\pi^2 r_c^4}\left\{\frac{1}{(NC_{D_i}\beta_r^2)^2} + \frac{1}{(C_{D_o}\delta^2)^2} + \frac{1}{(N\beta_e^2)^2}\left[C_5^2\left(\frac{1}{\delta_p^2} - 1\right) - \frac{2C_4C_5}{A(A-2)}\left(\frac{1}{\delta_p^A} - 1\right)\right]\right\} \qquad \text{Eq. 15}$$

where C_4 and C_5 are constants

A = flow parameter

δ_p = dimensionless overflow parameter.

After a complete analysis of the $D_{50\%}$ and the pressure drop equations presented in this section of the report, the OSU personnel selected the equations derived by Gerlach as a sound basis for the interpretation of the hydroclone pressure drop data. These equations have been compared with efficiency tests performed with the aid of inline sampling techniques in order to verify their use as a design criteria for hydroclones.

The application of these and other pertinent equations used to evaluate the pressure drop data will be presented in this section.

C. TEST PROCEDURE

A standard test procedure has been established for this investigation in order to insure accurate and repeatable test results. The test procedure outlined in the following paragraphs of this report is the one used to conduct all hydroclone pressure drop tests at OSU. The program in its entirety is quite simple and straight-forward to allow each test to be uniformly conducted by OSU personnel. The complete test procedure used while investigating the various hydroclone parameters from pressure drop data was as follows:

(a) The hydroclone, along with its parameters to be studied,

was assembled and mounted on the Hydraulic Test Stand.

(b) The Pressure Drop Stand was connected to the hydroclone unit under investigation.

(c) The flow meter and amplifier units were energized to allow ample time for warm up.

(d) The Hydraulic Test Stand was then started and time was allowed for the hydraulic fluid to be heated to an operating temperature of 120°F.

(e) After the fluid temperature reached 120°F., the flow controller valve was adjusted to produce full flow.

(f) The valves on the Pressure Drop Stand were then opened one at a time and the desired pressure drops within the hydroclone were displayed.

(g) After the pressure readings had been recorded at full flow rate, the flow was then reduced by 2.5 gpm; and the same pressure recordings were made. This procedure was followed until the flow rate had been reduced to approximately 10 gpm. Pressure readings below this flow rate were inaccurate due to small pressure readings within the hydroclone.

(h) The Hydraulic Test Stand was then turned off and the hydroclone was disassembled to permit the changing of the various hydroclone parameters required by the next test.

(i) The Hydraulic Test Stand was then re-started, and the test fluid was allowed to reach the operating temperature once again. After the fluid reached 120°F., steps (e) through (h) were merely repeated.

D. INVESTIGATION OF PARAMETERS

The investigation of the various hydroclone parameters and their effect on pressure drop was designed to afford a comprehensive study of a 1.00, 1.25, and 1.50 inch diameter hydroclone. Essentially, the test procedure consisted of holding all mediate variables constant while only altering the parameter under investigation. Care was taken to insure that in all test performances the same operating conditions prevailed.

For the first series of pressure drop tests, a 1.50 inch diameter hydroclone was selected. For parameter optimization of this hydroclone, a series of eight tests was conducted by OSU personnel using the test procedure previously outlined. In the following paragraphs, each test will be reviewed to furnish the reader a brief description of the tests as well as the primary purpose of each.

Test 1. The purpose of this test was to study the effect of variation of inlet diameter (single inlet) on the following:

(a) Pressure drop across the inlet, ΔP_i

(b) Inlet efficiency, N_i

(c) Calculated $D_{50\%}$ efficiency.

In order to determine the optimum inlet, different sized inlets ranging

in diameters from 1/4" to 7/16", in increments of 1/16", were tested holding all other hydroclone parameters constant. Pressure drop readings were then recorded at specified flow rate; and from these readings, (a), (b), and (c) were determined.

Test 2. The object of this test was to investigate the effect of different overflow diameters on the pressure drop across the overflow and the calculated $D_{50\%}$ value for the hydroclone. The overflow diameter was varied from 1/4" to 7/16". For each overflow tested, the dimensionless overflow pressure probe radius, δ_p, was carefully measured to assure accurate results when determining the dimensionless tangential velocity, V_o, and the pressure drop constant, C_3.

Test 3. The purpose of this test was to investigate the effects of circumferential multiple inlets on the calculated $D_{50\%}$ efficiency of the hydroclone. Inlets were arranged around the periphery of the inlet ring and pressure drop readings were recorded for the values of multiple inlets from 1 to 4.

Test 4. In this test, the effects of operating temperature on the calculated $D_{50\%}$ were investigated. The 1.50 inch diameter hydroclone was operated at fluid temperatures between 83° and 117°F. Pressure readings were then recorded at different temperature ranges to 117°F.

Test 5. The purpose of this test was again to investigate the effects of multiple inlets on hydroclone performance. Unlike Test 3, the inlets were placed axially on the inlet ring. The number of axial inlets varied from 1 to 4. Pressure readings were then recorded for each set of inlets, and the $D_{50\%}$ was calculated from the test data.

Test 6. This test was designed to study the variation of the cone angle on the efficiency of the hydroclone. The cone angles used in this investigation were the 8°, 10°, and 12°. From the pressure drop data, the $D_{50\%}$ ratings were calculated and recorded for each cone angle.

Test 7. This test was performed to determine the effect of the variation in underflow diameter on the efficiency rating of the hydroclone. The underflow diameters used in this test were varied from 5/32" to 8/32" in increments of 1/32". Pressure drop data were then recorded to determine a $D_{50\%}$ rating of the hydroclone for each underflow diamter.

Test 8. In this test, an attempt was made to determine the effects of a subcone on the calculated $D_{50\%}$ rating of a hydroclone. The same cones used in previous tests were again used with a 10° subcone attached to the original 10° cones used in Test 7. Pressure readings were recorded at various flow rates; and from this information, the $D_{50\%}$ was calculated.

Although the eight tests that have been described were conducted using a 1.50 inch hydroclone, identical tests and test procedures were performed on a 1.00 inch and a 1.25 inch diameter hydroclones. With the cumulative data from these tests, the over-all purpose of this study, to optimize hydroclone parameters from pressure drop data, was accomplished.

E. EVALUATION OF DATA

The results of the pressure drop tests were evaluated by correlating the experimental data, and by applying the test data to theoretical equations presented earlier. In this section, the theoretical equations are presented again, with special consideration given to their direct application as related to the evaluation of the pressure drop data. The efficiency equations and pressure drop equations are completely analyzed in order to illustrate their direct application to test results.

In order to help determine the most efficient inlet nozzle, the inlet efficiency was defined as follows:

$$N_i = \frac{v_c}{v_i} \qquad \text{Eq. 16}$$

where v_c = tangential velocity at $R = r_c$
v_i = inlet tangential velocity.
v_i can easily be derived by the well-known continuity equation as follows:

$$Q = Nv_iA_i \qquad \text{Eq. 17}$$

where Q = flow rate
N = number of inlets
A_i = inlet area
Solving for v_i and defining a dimensionless inlet size $\beta_r = r_i/r_c$, we have an expression for v_i in terms of the flow rate and the radius of the hydroclone.

$$v_i = \frac{Q}{N\pi\beta_r^2 r_c^2} . \qquad \text{Eq. 18}$$

If we now define $v_c\beta_e^2 = v_i\beta_r^2$, where β_e is defined as an effective dimensionless inlet radius, we have a similar expression for v_c.

$$v_c = \frac{Q}{N\pi\beta_e^2 r_c^2} . \qquad \text{Eq. 19}$$

Although v_c cannot be determined directly from Eq. 19 because the value of β_e is unknown, v_c can be determined experimentally from dynamic an static pressure measurements. The equations relating v_c and these pressure measurements can be expressed as follows:

$$P_{total} = P_{static} + P_{velocity} \qquad \text{Eq. 20}$$

$$P_{total} = P_{static} + \frac{\rho_L v_c^2}{2} \qquad \text{Eq. 21}$$

where ρ_L is the density of the fluid, $lb\text{-}sec^2/in^4$. Solving for v_c, we have the following expression:

$$v_c = \left(\frac{2\Delta P_v}{\rho_L}\right)^{\frac{1}{2}}, \; \Delta P_v = P_{total} - P_{static} \, . \qquad \text{Eq. 22}$$

Since a pitot tube measures total pressure, the difference between the pitot tube measurement and the static measurement is ΔP_v. Eq. 22 can be expressed as follows when using MIL-F-5606 hydraulic fluid:

$$v_c = 158.5 \quad \Delta P_v \qquad \text{Eq. 23}$$

where $\Delta P_v = lb/in^2$. Therefore, from Eqs. 18 and 23, an inlet efficiency can be determined for each inlet diameter investigated.

The following paragraphs will illustrate how the experimental data and the theoretical equations were combined in order to obtain the $D_{50\%}$ equation from pressure drop data.

Referring to Eq. 15, it can be seen that the theoretical equation for the pressure drop across a hydroclone is complicated since it involves a great many variables. Therefore, in order to facilitate the calculation of the $D_{50\%}$ size from the experimental data, an IBM 1620 digital computer was employed to obtain pertinent and accurate data curves to expedite tedious calculations. These curves were obtained by evaluating the pressure drop constant, C_3, for different values of the dimensionless overflow radius, δ_o, and the dimensionless flow parameter, A, with the aid of the IBM 1620 computer. The two equations, 24 and 27, that were programmed were as follows:

$$V_t = \frac{C_5}{G} - \frac{C_4 G^{-A+1}}{(A-2)} \qquad \text{Eq. 24}$$

where the constants C_4 and C_5 are constants of integration and were evaluated from boundary conditions. The values of these constants are as follows:

$$C_4 = \frac{(A-2)}{\frac{A\delta^{-A+2}}{2} - 1} \qquad \text{Eq. 25}$$

$$C_5 = 1 + \frac{1}{\frac{A(\delta)^{-A+2}}{2} - 1} \qquad \text{Eq. 26}$$

Eq. 24 describes the shape of the tangential velocity curve as a function of the radius of the hydroclone. The other equation programed was the pressure drop constant; this equation can be expressed as follows:

$$C_3 = \left[\left(\frac{C_5^2}{2}\,\frac{1}{(\delta_p)^2} - 1\right) + \frac{2C_4C_5}{A(A-2)}\left(1 - \frac{1}{(\delta_p)^A}\right)\right] \qquad \text{Eq. 27}$$

Eq. 27 was programed and the different values of C were computed for values of A from 2.5 to 4.0 and δ_p ranging from .10 to .35. These ranges were determined from previous investigations and were proven to be a valid range for both the flow parameter and the dimensionless overflow radius for hydroclones with flow capacities up to 40 gpm.

From the computer results of Eq. 27, important curves were compiled relating C_3 to the dimensionless parameters A and δ_p. (See Fig. 35 and Fig. 36.) Also, since A is a flow parameter and describes the tangential profile over the radius of the hydroclone, a plot of the dimensionless tangential velocity, V_o, versus the flow parameter, A, can be constructed. (See Fig. 37.) In order to illustrate more clearly the use of these curves, Eq. 14 is rearranged and presented here in a different form as follows:

$$C_3 = \frac{N^2\pi^2\beta_e^2 r_c^4}{\rho_L Q^2} \cdot \Delta P_c \qquad \text{Eq. 28}$$

But since $v_c = \frac{Q}{N\beta_e^2 r_c^2}$, Eq. 28 reduces to:

$$C_3 = \frac{\Delta P_c}{\rho_L v_c^2} \qquad \text{Eq. 29}$$

Eq. 29 gives an important relationship since ΔP_c and v_c can be measured experimentally from hydroclone pressure drop data. With these values available, C_3 can be determined experimentally for each flow rate and each hydroclone configuration. Using MIL-F-5606, with $\rho_L = .80 \times 10^{-4}$ lb-sec^2/in^4, Eq. 29 becomes:

$$C_3 = 1.25 \times 10^4 \cdot \frac{\Delta P_c}{v_c^2} \qquad \text{Eq. 30}$$

With the use of Eq. 30, the dimensional flow parameter can be determined from the C_3 versus A curve.(Fig. 35). After this value of A has been determined, another curve (Fig. 37) is used to find the value of V_o. This value of V_o determines the tangential velocity profile that exists for a certain flow rate in the hydroclone under investigation. This is the value of V_o that must be used in Eq. 8 to determine the actual $D_{50\%}$ efficiency of the hydroclone.

One point should be clarified as to the use of the curves shown in Figs. 35 and 37. These curves were presented here merely for illustrative purposes and are only valid when used with a hydroclone with $\delta = .25$. Additional C versus A curves were obtained from computer results by OSU personnel and were used to analyze hydroclone configurations with different sized overflow diameters.

1. Analysis of $D_{50\%}$ Equation

The $D_{50\%}$ equation will be completely analyzed here to provide the reader with a working knowledge of all variables involved and to further facilitate the determination of a $D_{50\%}$ rating for a certain hydroclone from pressure drop data. The complete $D_{50\%}$ equation presented earlier is reproduced again in order to illustrate its use in determining a particle size efficiency rating for different hydroclones.

$$D_{50\%} = \frac{3K_1 N\beta_e^{\,2}}{V_o}\left[\frac{\pi\mu r_c^{\,3}\tan\varphi/2}{Q(\rho_s-\rho_L)(1-\delta)}\right]^{\frac{1}{2}} \qquad \text{Eq. 8-A}$$

where $D_{50\%}$ = diameter (microns) separation with 50% efficiency
K_1 = conversion factor, 1.275×10^4
β_e = effective dimensionless inlet radius, $\beta_e = \frac{v_i}{v_c}\beta_r$
V_o = dimensionless tangential velocity, $V_o = v_o/v_c$
μ = absolute viscosity, lb-sec/in^2
r_c = radius of hydroclone, inches
Q = flow rate, gpm
φ = cone angle, degrees
$\rho_s-\rho_L$ = relative density, lb-sec^2/in^4
δ = dimensionless overflow radius, $\delta = r_o/r_c$.

To insure proper use of the equations presented in this section for the determination of the $D_{50\%}$ size for a particular hydroclone, the following simplified procedure is given:

(a) Obtain ΔP_v and ΔP_c from the pressure drop data.
(b) Use Eq. 23 to determine v_c.
(c) Compute C_3 from Eq. 30.
(d) Read the value of A from Fig. 35, making sure that $\delta = .25$ and that both δ and δ_p are within the range of the graph.
(e) With the value of A, using Fig. 37 to determine V_o.
(f) Then finally, with this value of V_o, use Eq. 8-A to compute $D_{50\%}$.

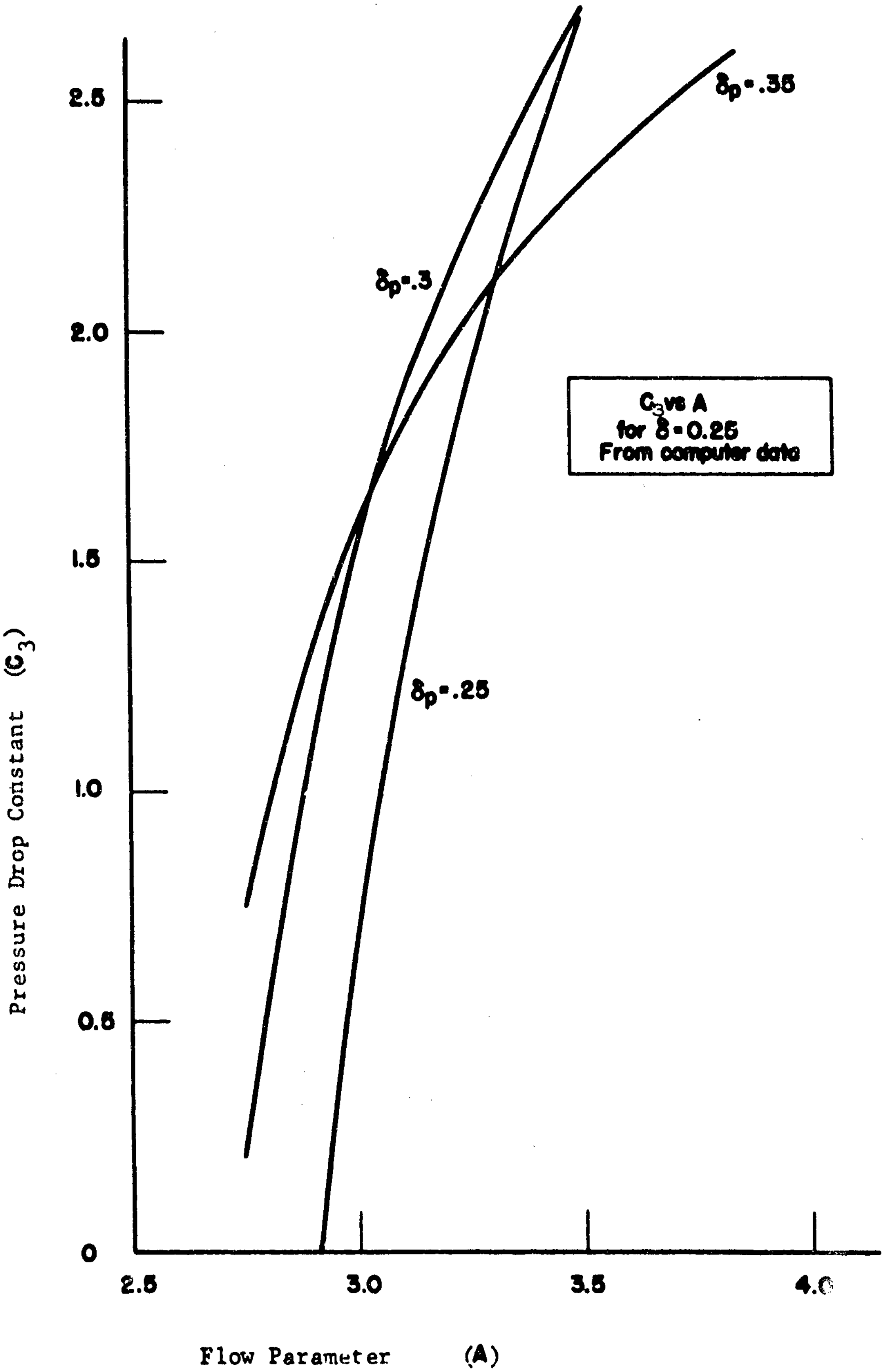

Fig. 35. Curves (plotted from computer results) Relating C_3 to the Parameters A and δ_p with $\delta = .25$.

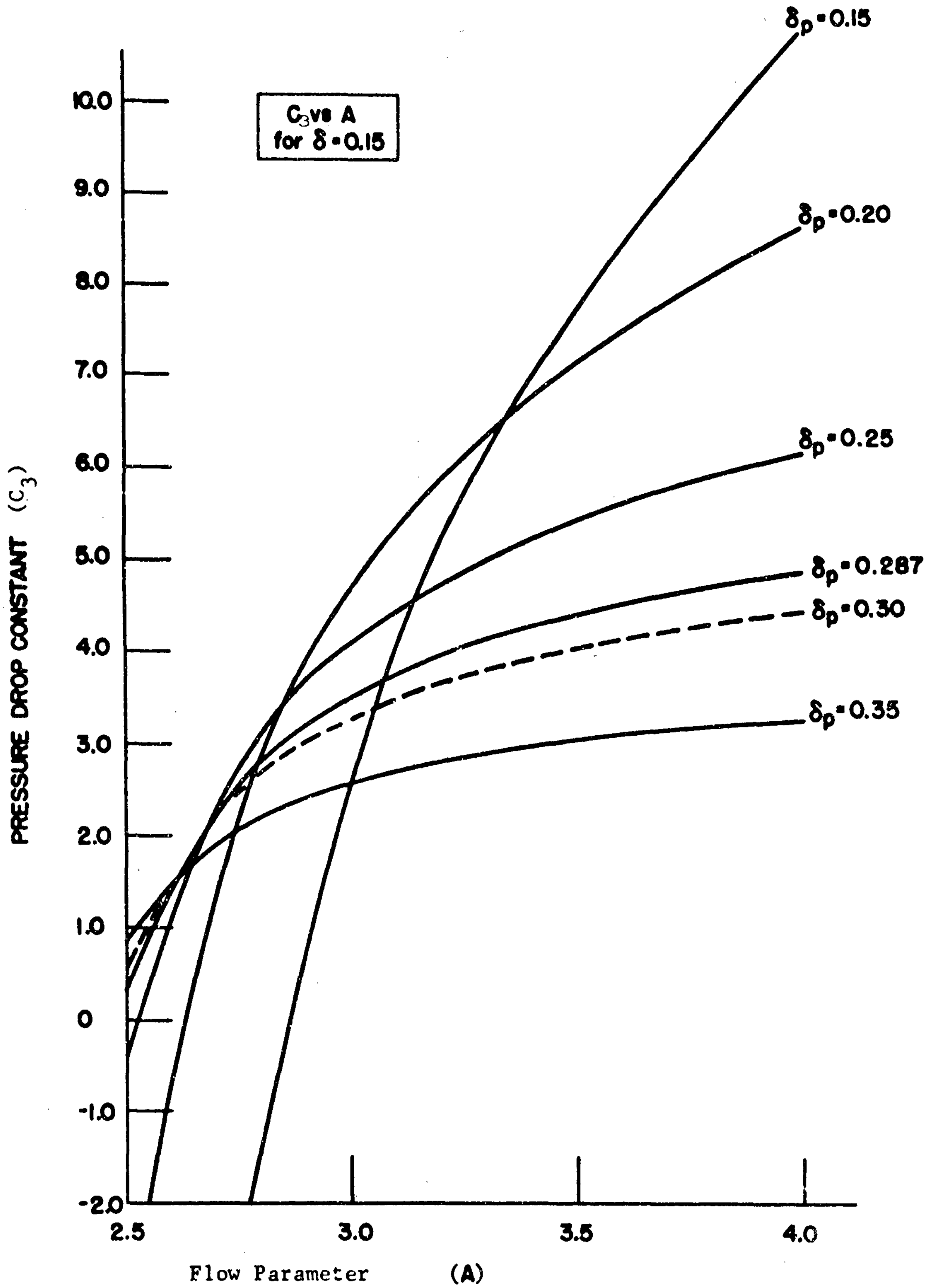

Fig. 36. Curves (plotted from computer results) Relating C_3 to the Parameters A and δ_p with $\delta = .15$.

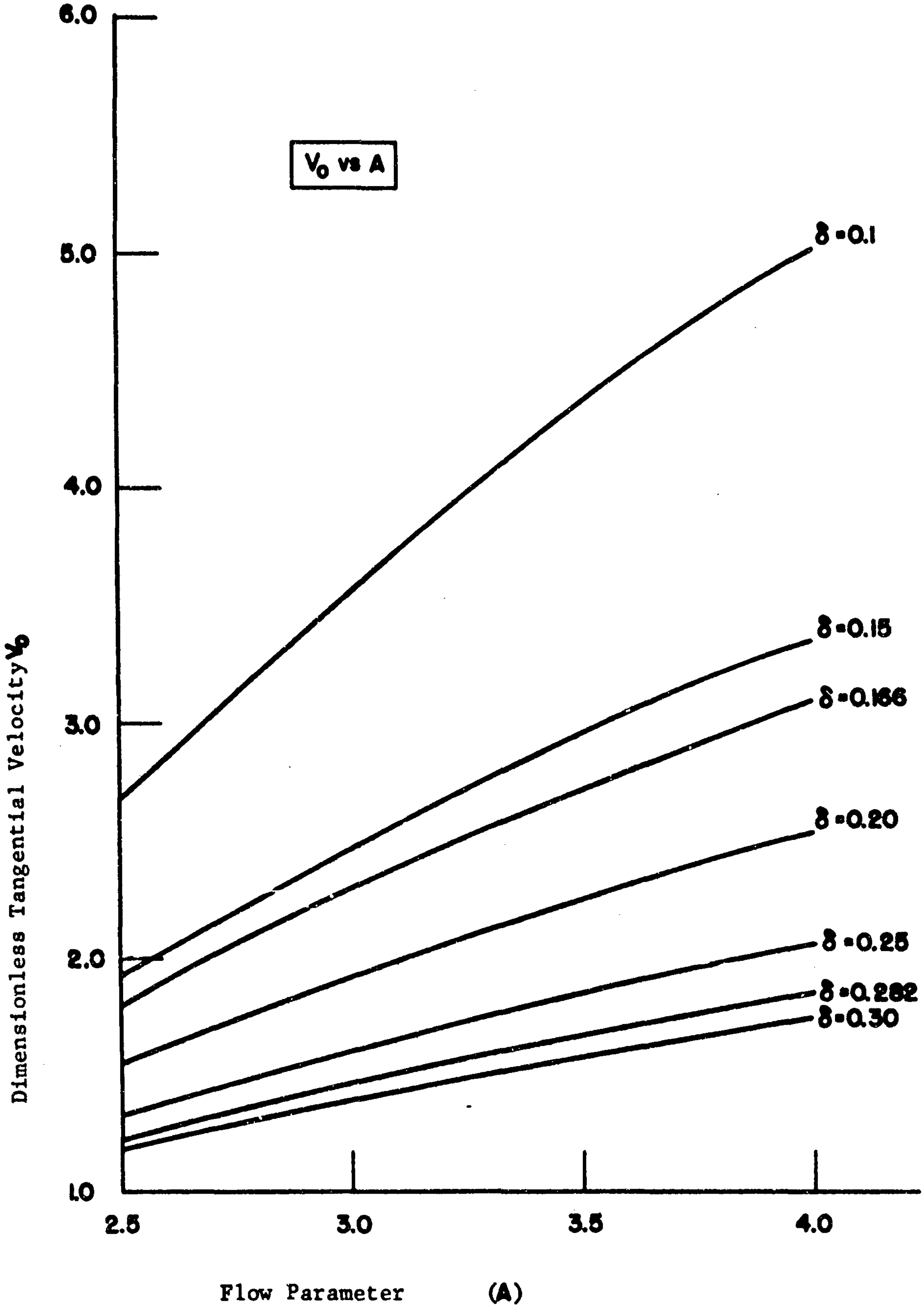

Fig. 37. Curves (plotted from computer results) Relating V_0 to A and δ.

F. RESULTS AND CONCLUSIONS

The design criteria, as previously determined by OSU personnel, was aimed at producing the most efficient hydroclone with the least pressure drop. Therefore, in order to optimize any hydroclone parameter from pressure drop tests, $D_{50\%}$ versus ΔP_T curves were plotted and each parameter compared on this basis.

Referring to Figs. 38, 39, and 40, we have three of the most important results using a 1.50 inch hydroclone. As mentioned earlier in this report, the pressure data might prove useless for optimizing certain parameters; this proved to be the case as the cone angle, diameter of underflow, and the subcone investigations were of no value as far as pressure drop studies were concerned. The plots of $D_{50\%}$ versus ΔP_T for the inlet diameter and overflow tests are presented in Figs. 38 and 39. The results from these curves show that a 5/16" inlet and 1/4" overflow produced the most efficient results with the least power. Pressure drop tests on the 1.5 inch hydroclone did reveal quite convincingly that single inlets were more efficient than multiple inlets (See Fig. 40.) These same results were observed during similar circumferential multiple inlet tests with the 1.5 inch hydroclone. After these inlet results, OSU personnel felt that conclusive evidence had been presented against the use of multiple inlets, and no further investigations concerning these inlets were pursued.

The results of the curves presented in Figs. 41 and 42 show that an optimum inlet and overflow for the 1.25 inch hydroclone to be 9/32" and 5/16", respectively.

After each hydroclone had been optimized to the best of its ability from pressure drop tests, each unit was then compared with the other two in order to determine the optimum hydroclone diameter. The result of these findings is shown in Fig. 43. The results of these tests show the 1.5 inch hydroclone to be the best unit from a standpoint of producing the maximum efficiency with the least pressure drops.

The conclusions reached by OSU personnel concerning the use of pressure drop data as a design criteria for hydroclones was that pressure drop studies in conjunction with Eq. 8 proved to be a feasible means of selecting optimum inlet, overflow and hydroclone diameters. But as far as optimizing a complete hydroclone, pressure drop studies need to be supplemented by efficiency studies.

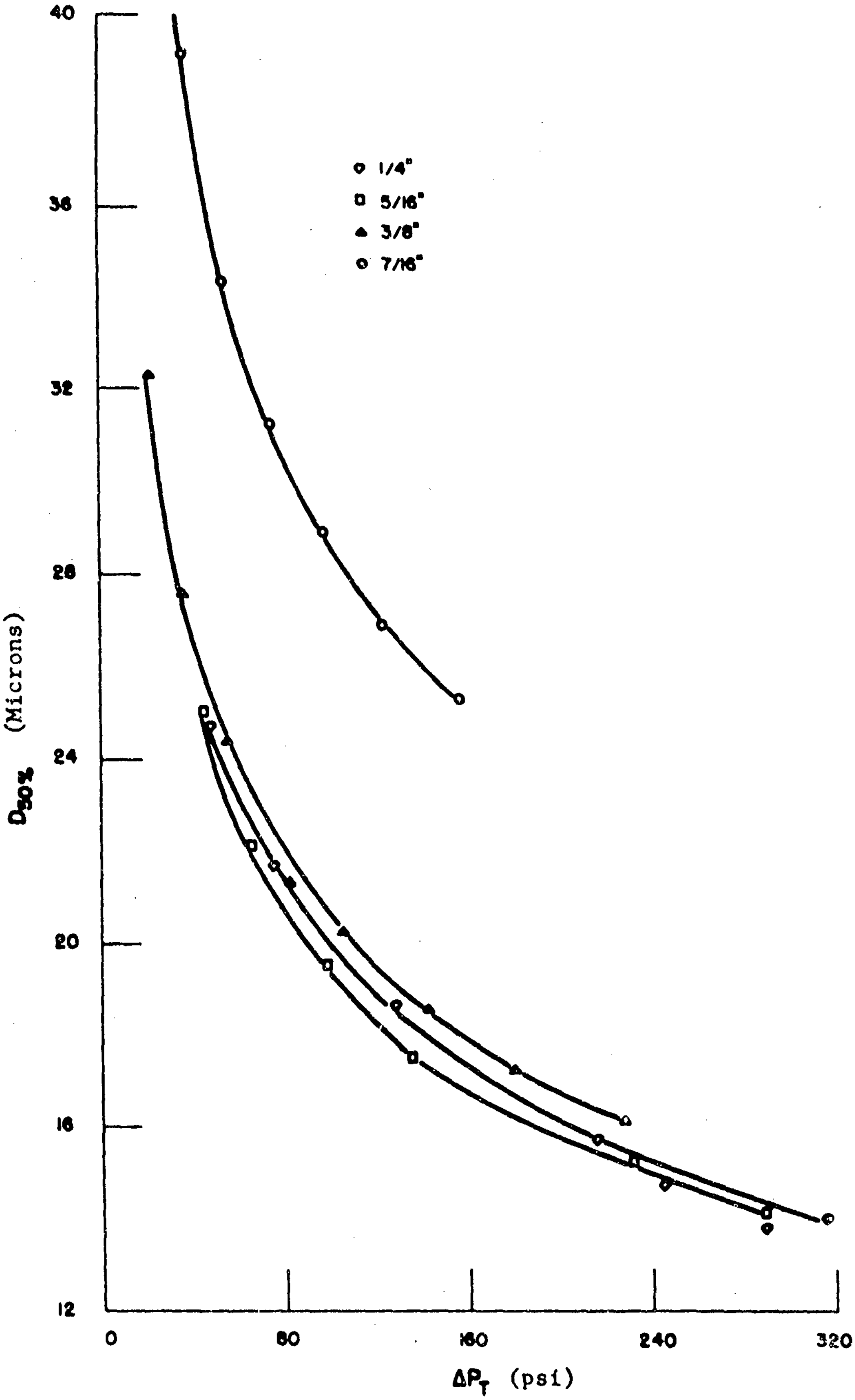

Fig. 38. Graph of $D_{50\%}$ versus ΔP_T as the Inlet Diameter is Varied on the 1.5 inch Hydroclone.

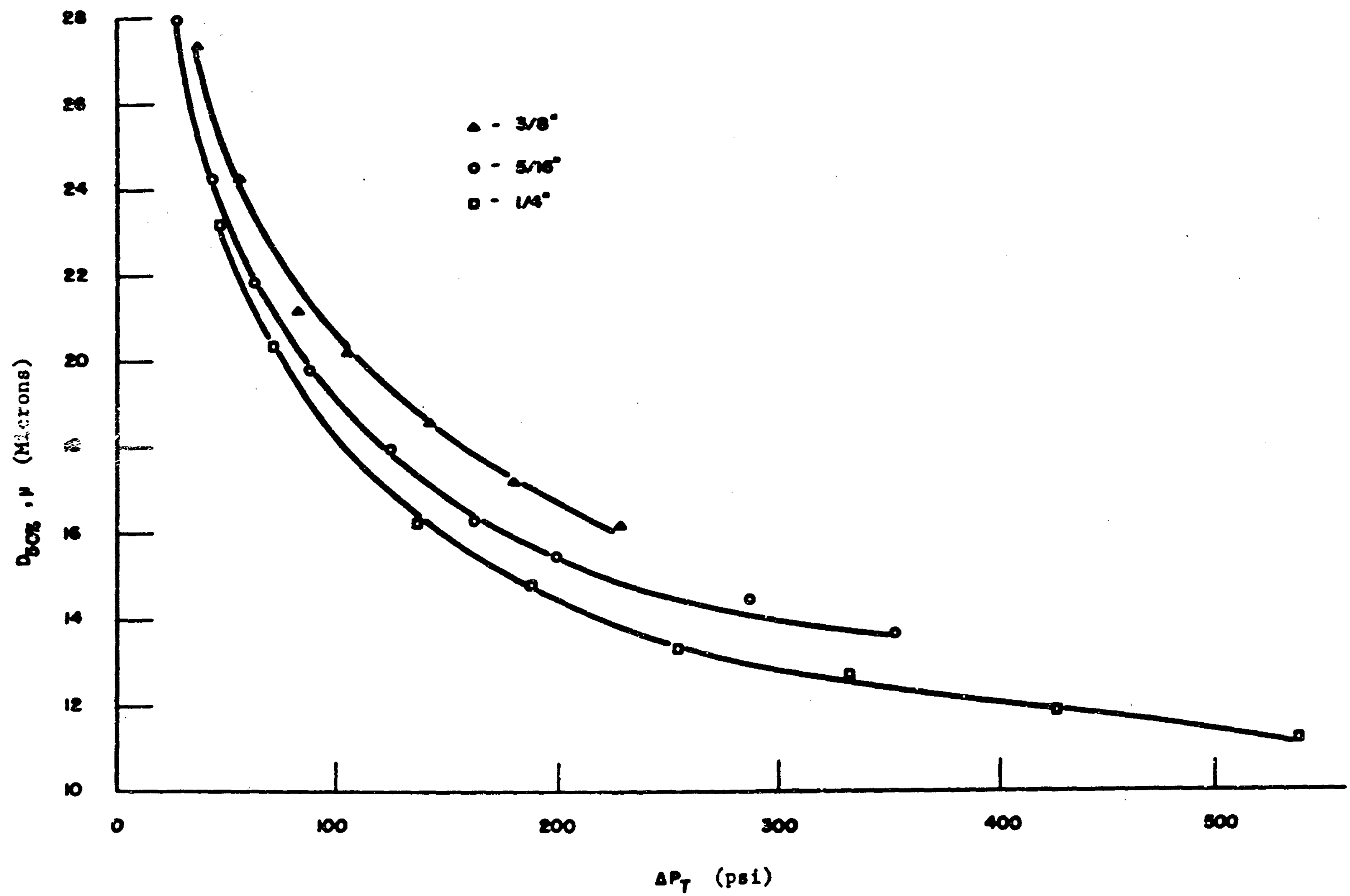

Fig. 39 Graph of $D_{50\%}$ versus ΔP_T as the Overflow Diameter is Varied on the 1.5 inch Hydroclone.

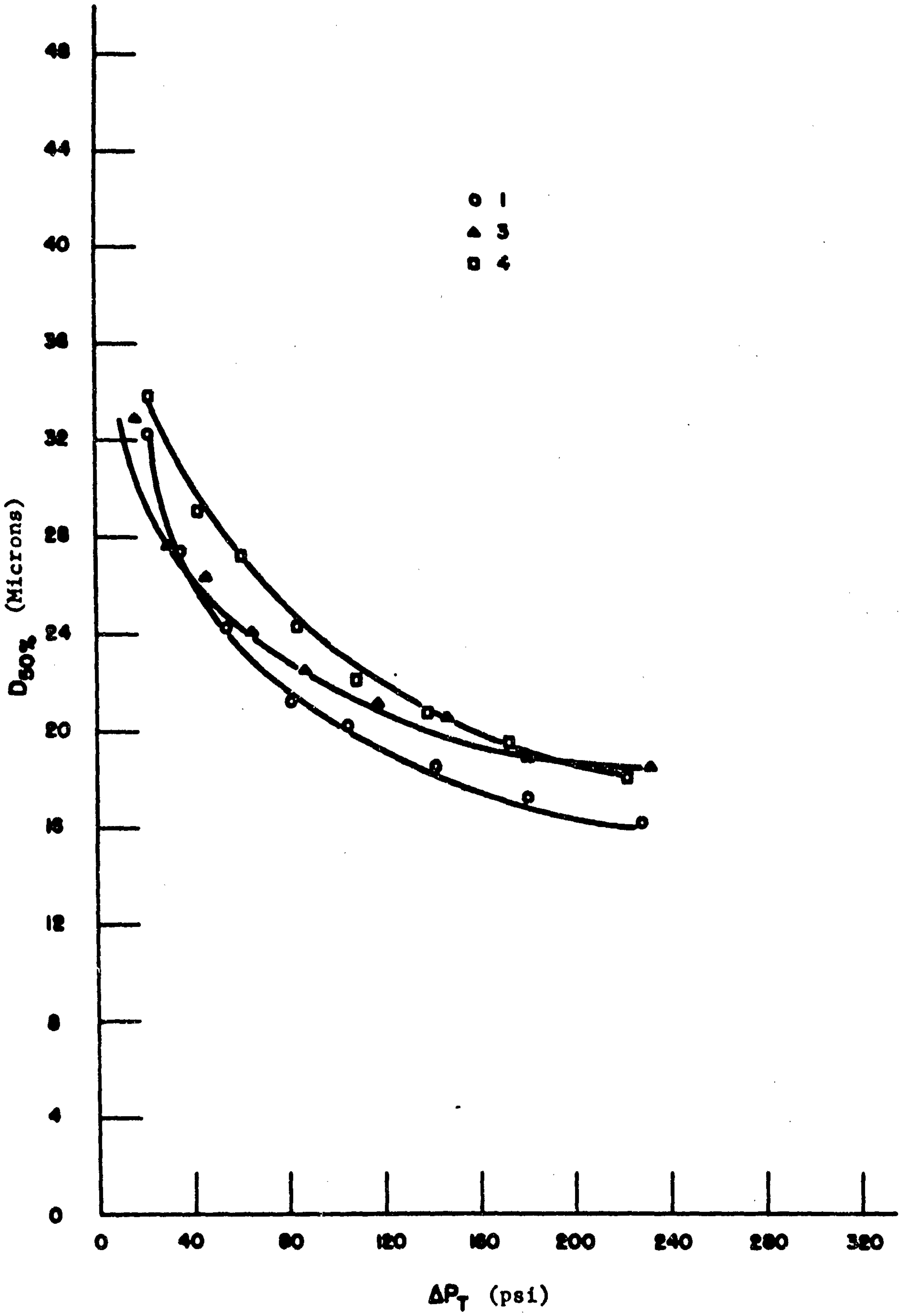

Fig. 40. Graph of $D_{50\%}$ Versus ΔP_T as the Number of Axial Inlets are Varied from 1 to 4.

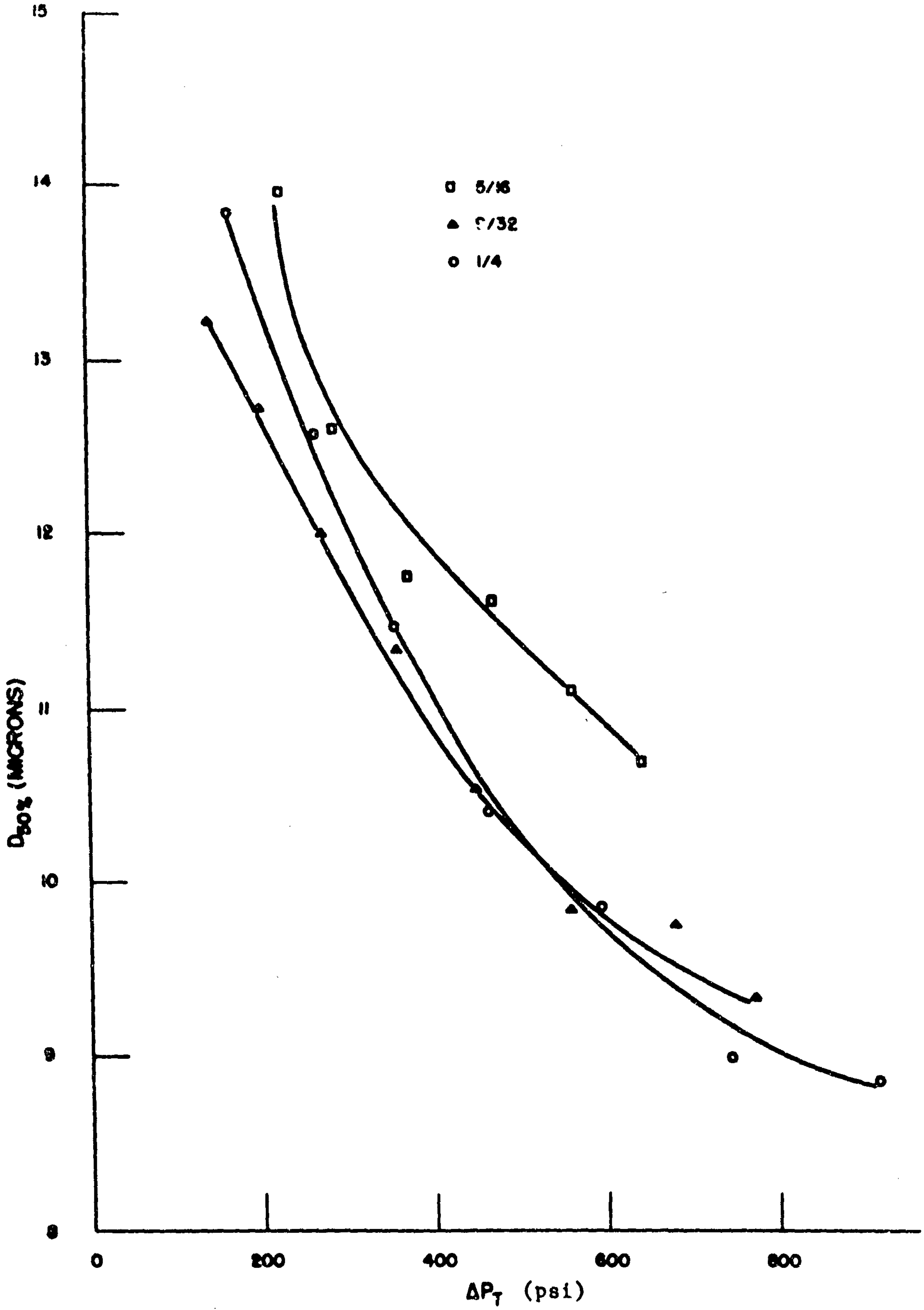

Fig. 41. Graph of $D_{50\%}$ Versus ΔP_T as the Inlet Diameter is Varied on the 1.25 inch Hydroclone.

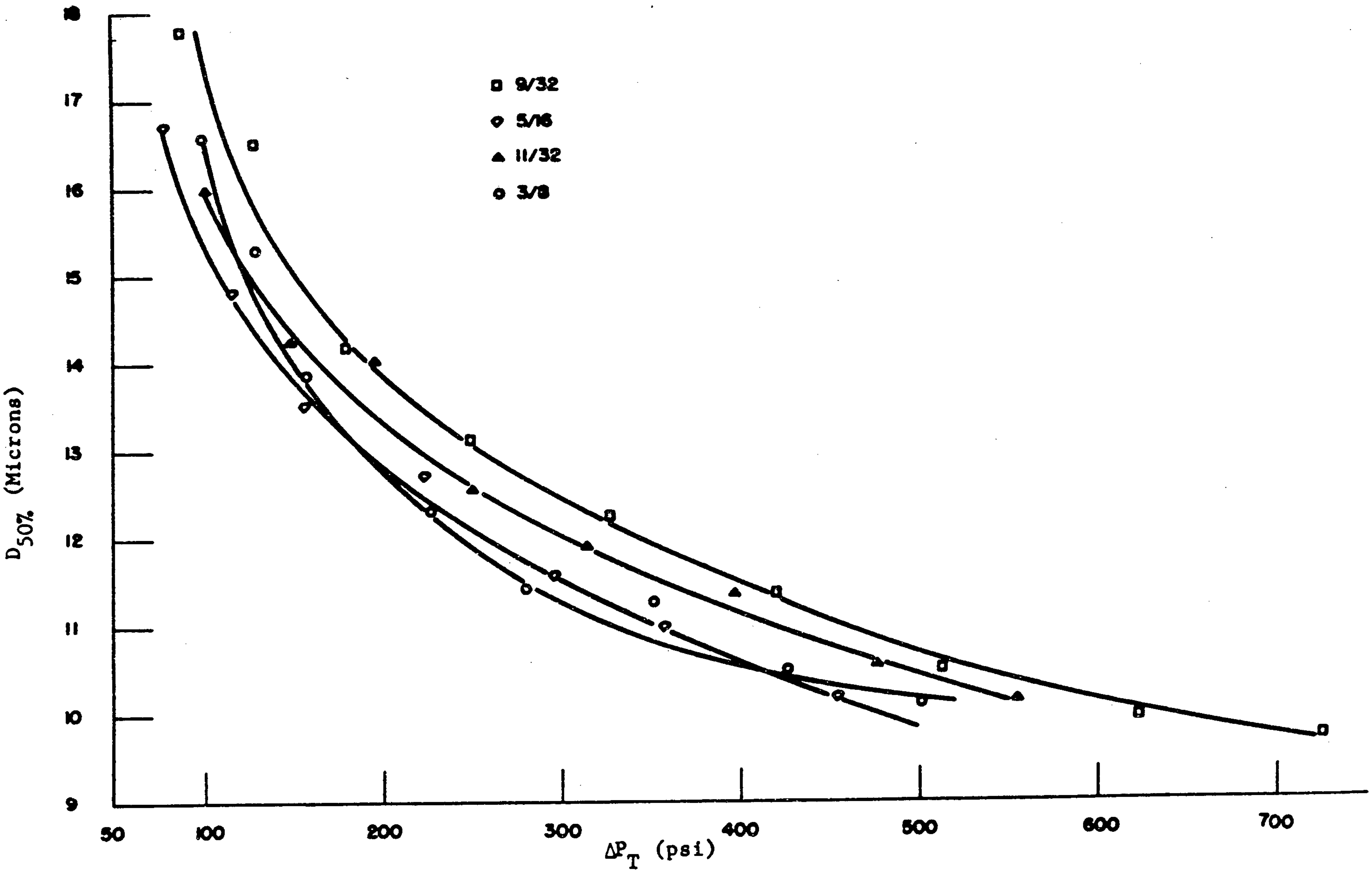

Fig. 42. Graph of $D_{50\%}$ Versus ΔP_T as the Overflow Diameter is Varied on the 1.25 inch Hydroclone.

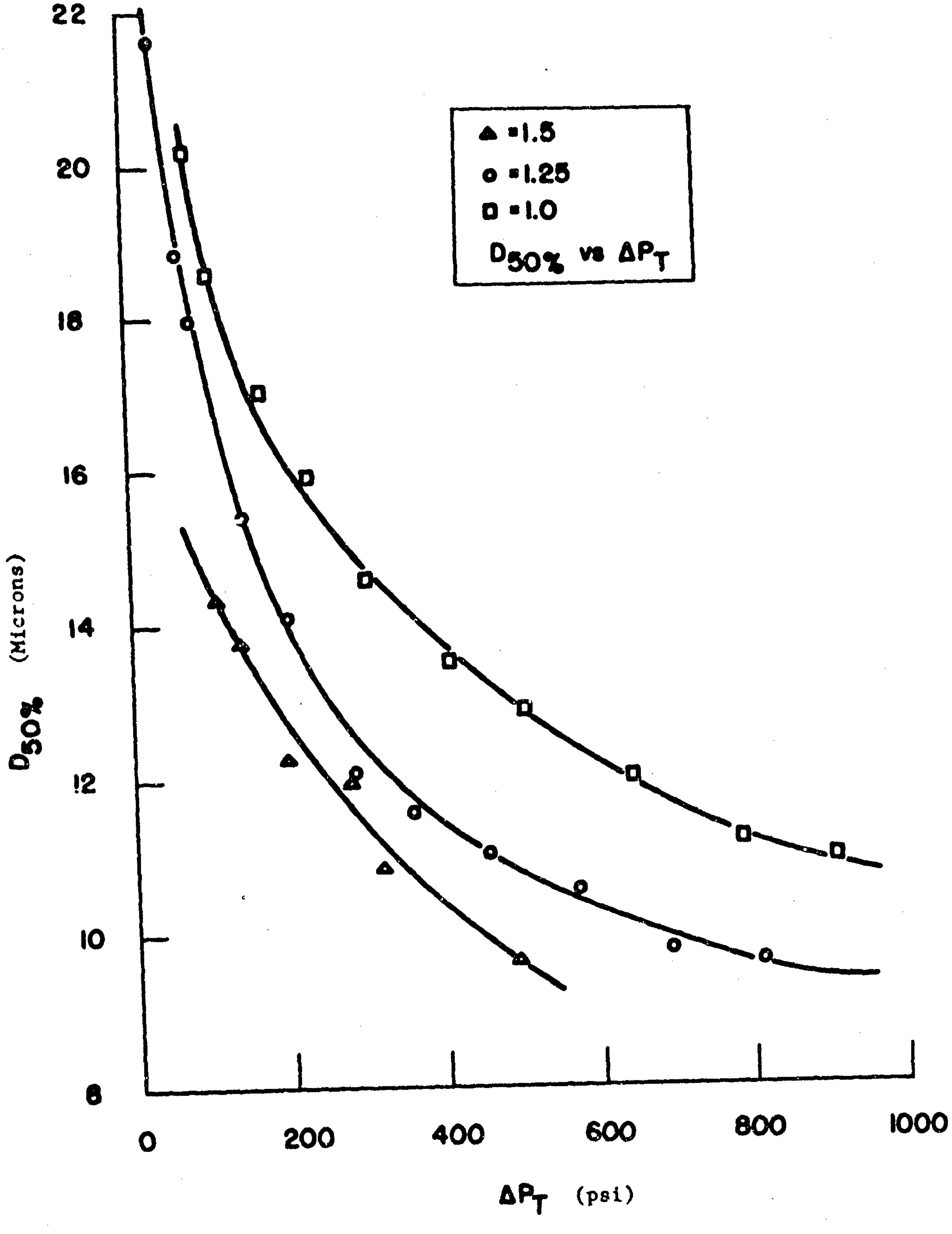

Fig. 43. Graph of $D_{50\%}$ Versus ΔP_T for Comparison of 1.00, 1.25, and 1.50 inch Hydroclone.

SECTION VI

SEPARATION EFFICIENCY TEST PROGRAM

A. INTRODUCTION

This phase of the hydroclone testing program was conducted in order to establish the optimum hydroclone parameters from the standpoint of separation efficiency. All of the configuration parameters used in the pressure drop analysis were investigated in the efficiency tests. These include hydroclone diameter, overflow diameter, inlet diameter, and diameter of the underflow. The two parameters, cone angle and diameter of the underflow, could not be investigated properly by a pressure drop study but were effectively analyzed from efficiency data. These two parameters are both directly connected with the cone configuration.

Hydroclone separation efficiency is dependent on particle size, relative density of the particles and the fluid, and on the size distribution of the contaminant in the system. Therefore, it is necessary to define the term efficiency as used in this report. Two efficiency numbers will be used in order to obtain a better understanding of the performance of the unit.

"Range Efficiency" will be used to describe the hydroclone performance in the range above a specified particle size. This is calculated by taking the difference between the upstream and downstream counts at a specified micron setting and then dividing this value by the upstream count. This efficiency will tell what per cent of the particles above a specified diameter are being separated from the fluid.

"Specific Efficiency" will be used when describing the separation at a specified micron size. To arrive at this number, the difference between sets of figures of the downstream particle counter are subtracted from the difference of the corresponding sets of figures of the upstream counter. The resulting difference is then divided by the upstream difference in order to obtain this efficiency. Each particle counter displays four sets of figures, where each set of figures is a count of all particles above a particular size calibration setting.

B. EFFICIENCY TEST PROCEDURE

Before an extensive efficiency study could be made, a definite procedure for testing had to be designed in order to assure the best possible results. The general procedure was to vary the size of the parameter being investigated until a peak in separation efficiency was reached, being careful to hold all other variables constant. When the peak was reached, the size increment of the parameter was made smaller until the optimum efficiency for that parameter was attained. All efficiency tests were made in the following order:

(a) The assembled test hydroclone of a particular configuration was installed on the Hydraulic Test Stand. The test stand

was started and allowed to reach the testing temperature of 120°F.

(b) The injection pump was started and switched to inject clean fluid. This allowed for the test flow conditions to be established prior to the actual injection of contaminant particles into the system.

(c) The flow valves on the HIAC Particle Counter stand and the inline sample ports on the test stand were opened for calibration of the counters.

(d) Flow through the hydroclone was adjusted to the desired rate for the specific test being run.

(e) With the system flow and pressure constant, the flow through the upstream and downstream HIAC counters was set to identical values, usually 1 gpm.

(f) The metering tube on the microcell outlets of each HIAC counter was adjusted until each had a flow rate through its counting mechanism of 84 drops per minute. Eighty-four drops per minute corresponds exactly to one milliliter per minute using MIL-F-5606 hydraulic fluid.

(g) With all flow adjustments made, the contaminant slurry reservoir was charged with a measured amount of AC Fine Test Dust, and the stirring motor was started to achieve and maintain a homogeneous mixture.

(h) The counters were then switched to their operate position to check the background contamination level of the test fluid. The one-half micron control filter incorporated in the test system has virtually eliminated any error due to background contamination.

(i) The contaminant injection circuit of the injection system was then actuated for the test run. The particle counters were zeroed and then operated for a five minute injection period before they were stopped and the test results recorded. Representative results of the tests are presented in the graphs included in Figs. 44 to 49.

C. PARAMETER INVESTIGATION

1. Hydroclone Diameter

The object of this series of tests was to obtain the optimum hydroclone diameter based on an efficiency study. In order to make a complete evaluation, two types of tests were conducted. The configuration parameters were held constant for both series of tests with the hydroclone diameter being changed from 1.00 inches to 1.50 inches by 1/8 inch increments. The first series of tests were run at a constant flow rate, and the second series was conducted by holding the pressure drop across the cone at 250 psi. An optimum hydroclone diameter of 1.375 inches was arrived at as a result of the tests.

2. Inlet Diameter

After obtaining the optimum hydroclone diameter, the most efficient inlet was found by holding all configuration parameters constant

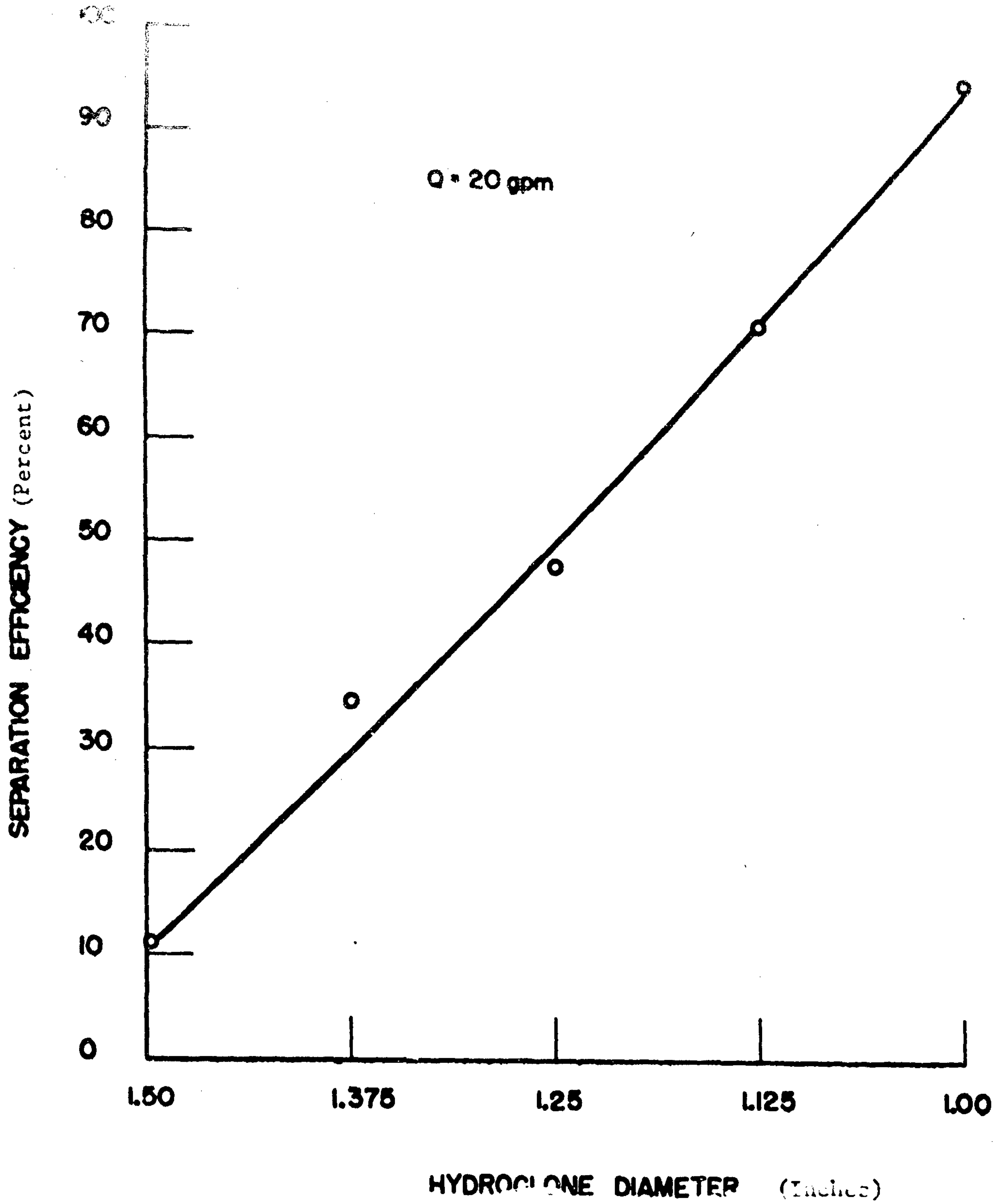

Fig. 44. Separation Efficiency for 6 Micron Particles Versus Cone Diameter with Flow Rate Held Constant.

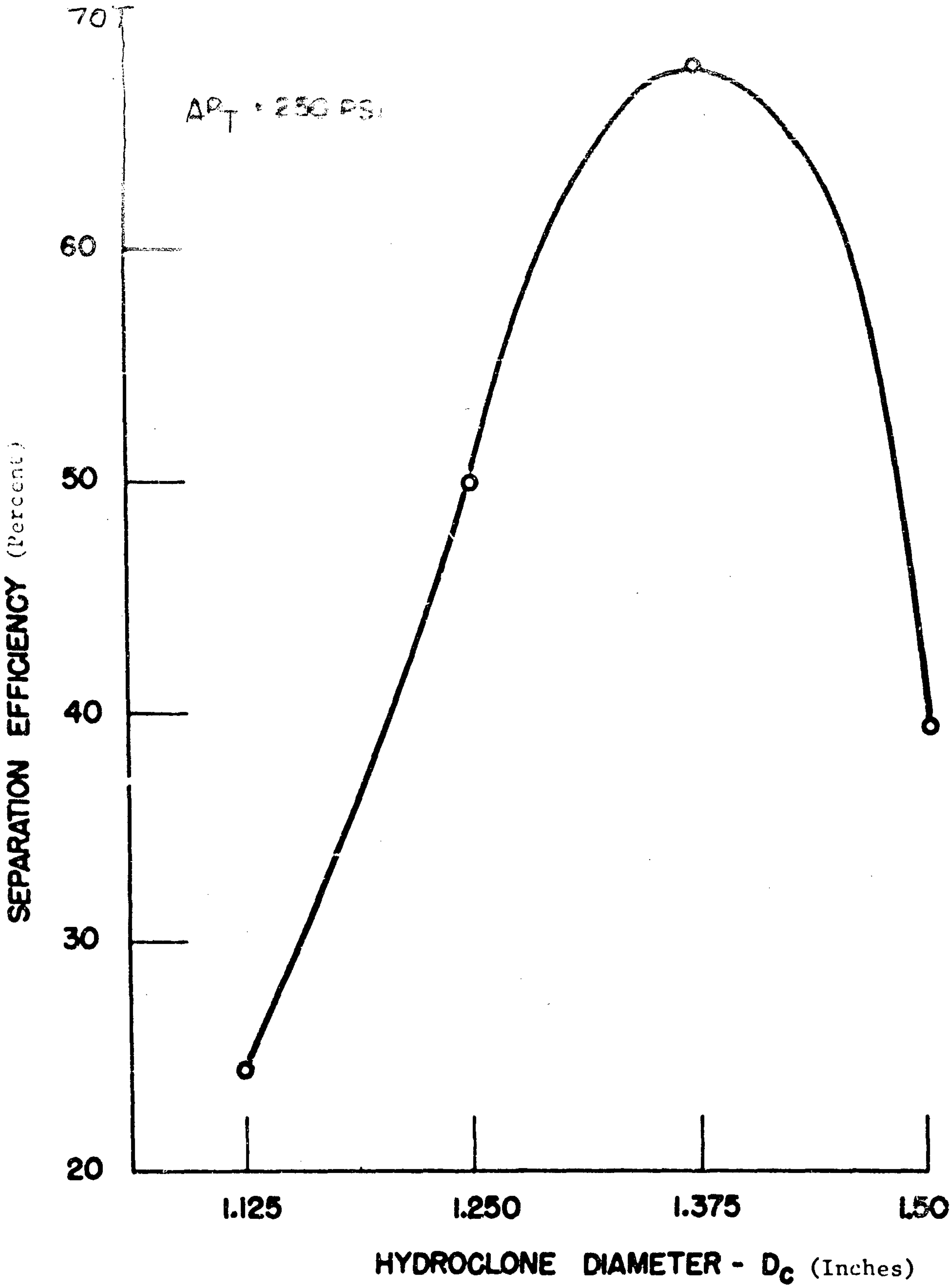

Fig. 45. Separation Efficiency for 6 Micron Particles Versus Cone Diameter with Pressure Drop of 250 psi Maintained Across the Hydroclone.

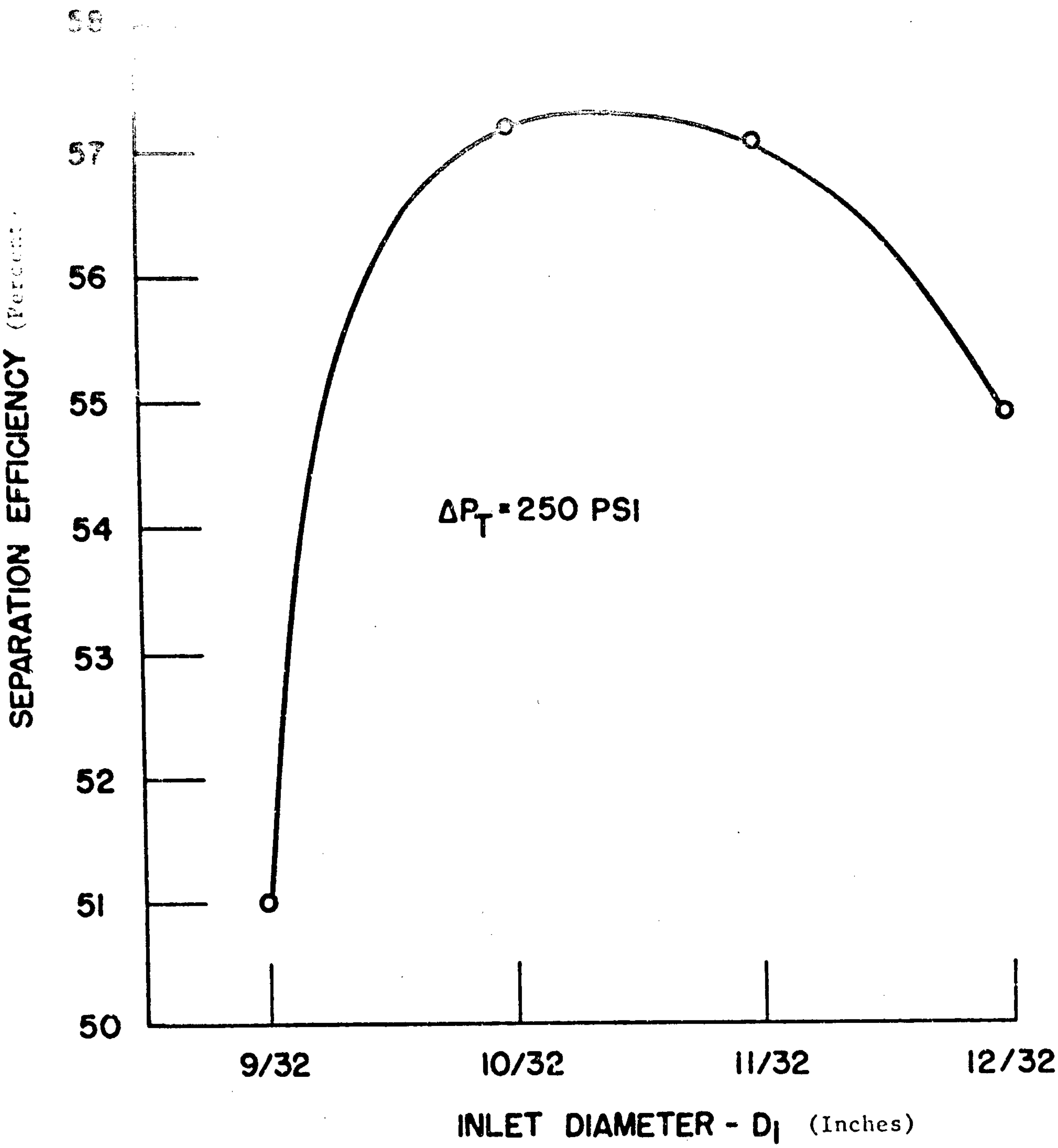

Fig. 46. Separation Efficiency for 6 Micron Particles Versus Inlet Diameter with Pressure Drop of 250 psi Maintained Across the Hydroclone.

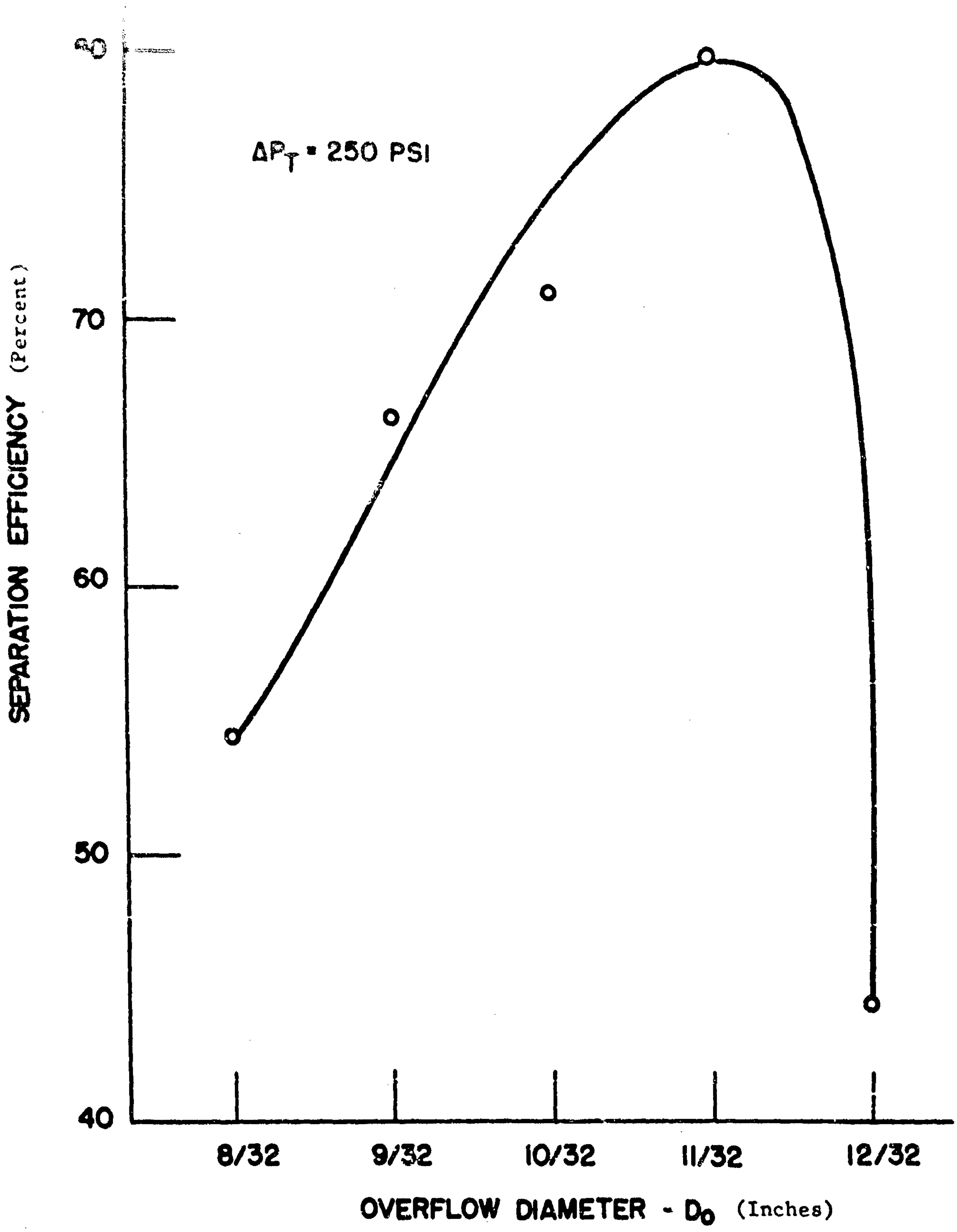

Fig. 47. Separation Efficiency for 6 Micron Particles Versus Overflow Diameter with Pressure Drop of 250 psi Maintained Across the Hydroclone.

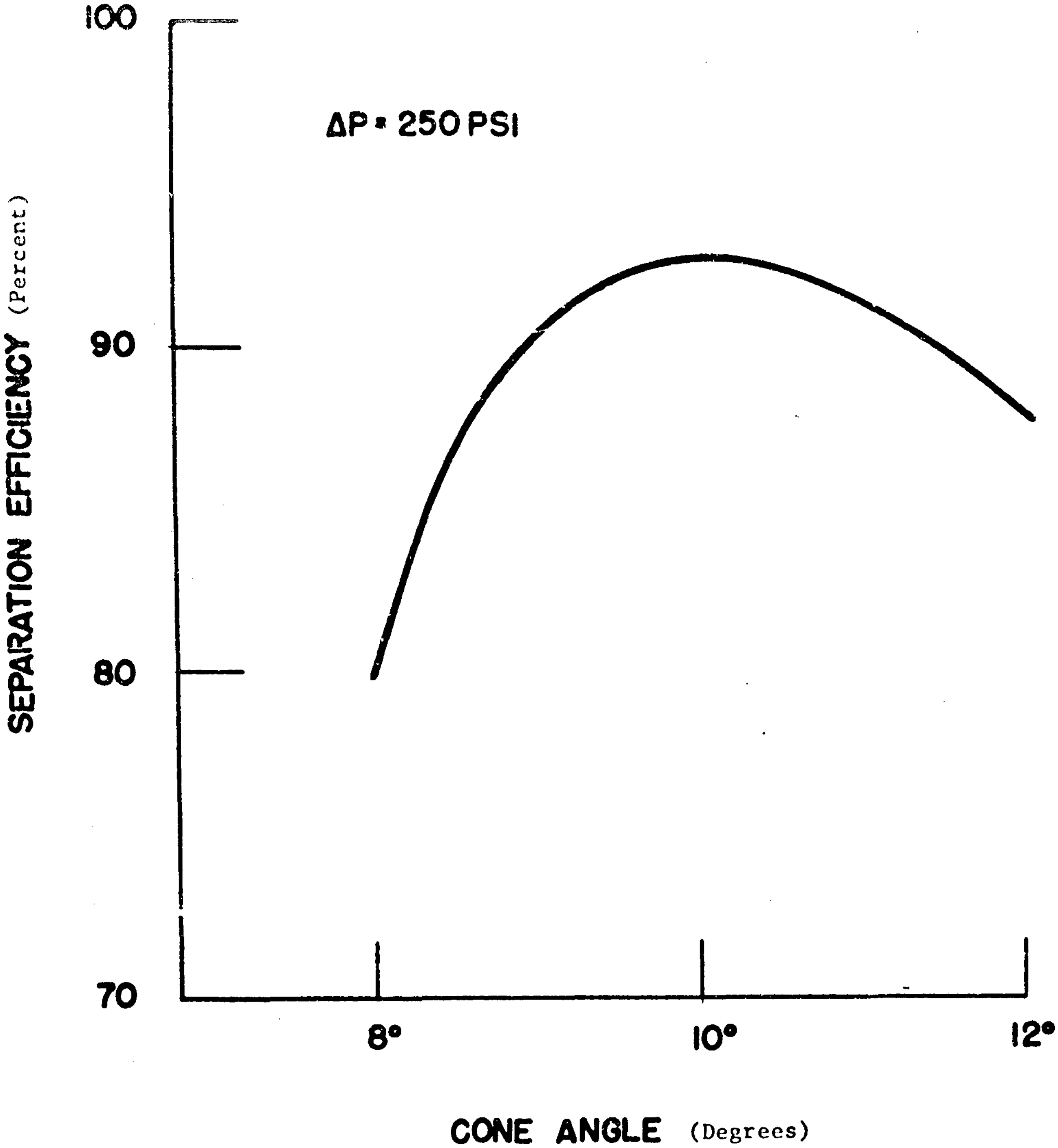

Fig. 48. Separation Efficiency for 6 Micron Particles Versus Cone Angle with Pressure Drop of 250 psi Maintained Across Hydroclone.

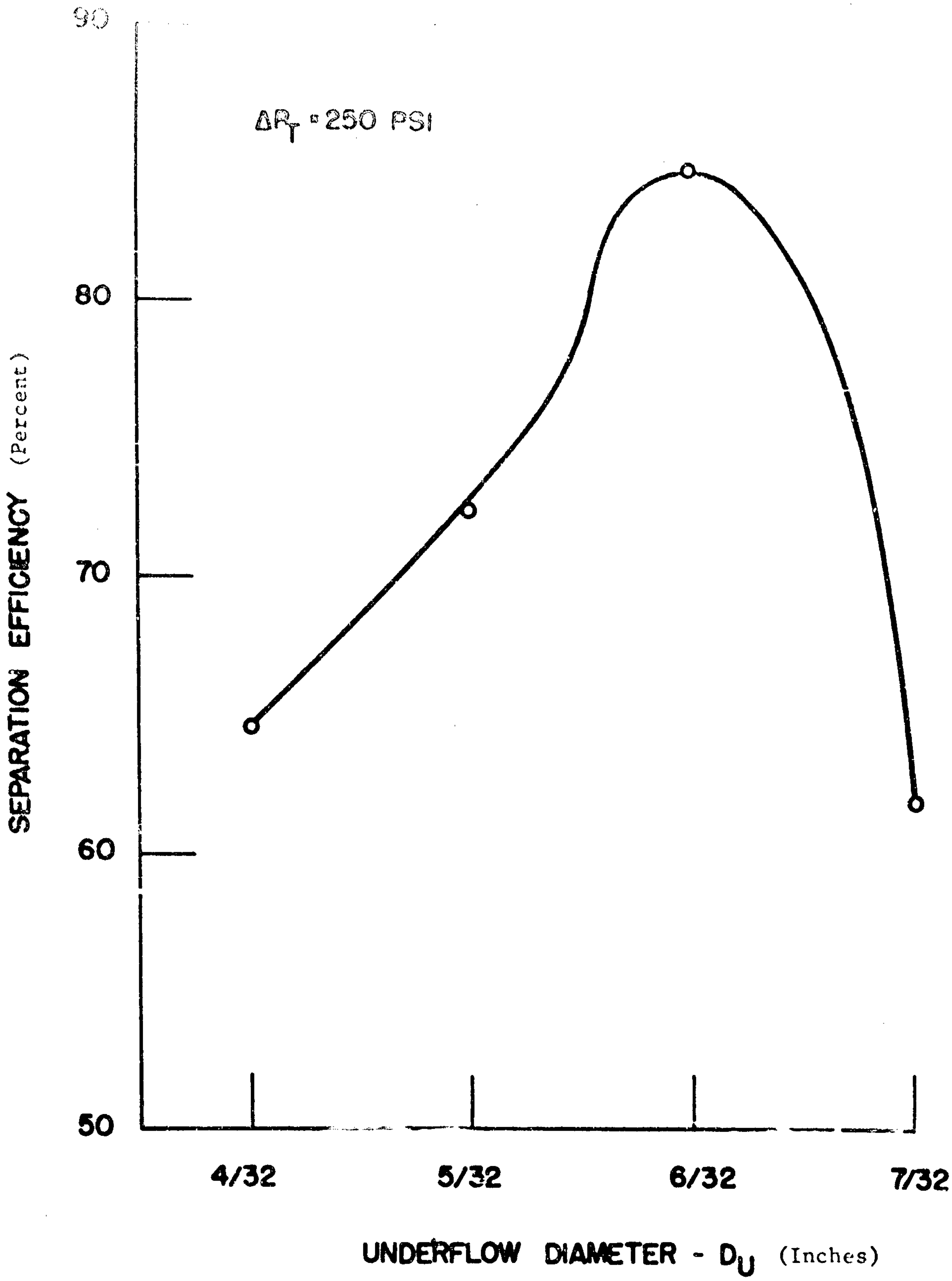

Fig. 49. Separation Efficiency for 6 Micron Particles Versus Underflow Diameter with Pressure Drop of 250 psi Maintained Across Hydroclone.

and varying the inlet size from 9/32 inch to 3/8 inch. The pressure across the unit was held constant at 250 psi. As dictated by the pressure drop study, single inlets were used for the tests.

3. Overflow Diameter

The next parameter investigated was the vortex finder or overflow. The 1.375 inch hydroclone was used holding all configuration parameters constant and varying the overflow size from 8/32 inch to 12/32 inch. The total pressure drop across the hydroclone was held at 250 psi for all tests involving variations of the overflow diameter.

4. Cone Angle

The optimum cone angle was determined by changing the angle between 8° to 12°. All other configuration parameters of the 1.375 inch hydroclone were fixed, and the total pressure drop was held at 250 psi.

5. Underflow diameter

The last configuration parameter investigated was the size of the underflow. With all parameters being held constant and the pressure drop fixed at 250 psi, the size was varied from 4/32 inch to 7/32 inch to determine the optimum.

D. EVALUATION OF TEST DATA

Before the efficiency calculations could be made, the results from each test were first analyzed for consistency. For all critical points, the points bordering on the peak of the optimization curves, at least two consecutive verification tests were conducted to assure correct and accurate results.

The actual calculations were made by first averaging the results of the consecutive verification tests and then calculating the Specific and Range Efficiencies. In order to best show the calculations and the difference between the two efficiencies, an example will be given for the purpose of demonstration.

Particle Diameter	Upstream Average	Downstream Average
6 microns	$U_1 = 2000$	$D_1 = 1000$
9 microns	$U_2 = 1000$	$D_2 = 400$
15 microns	$U_3 = 500$	$D_3 = 100$
20 microns	$U_4 = 100$	$D_4 = 25$

Range Efficiency (above 6 microns) $$E_r = \frac{U_1 - D_1}{U_1} = \frac{2000-1000}{2000}.$$

The same method was used for 9, 15 and 20 micron range efficiencies.

Specific Efficiency at 7 microns

$$E_s = \frac{(U_1-U_2-(D_1-D_2)}{(U_1-U_2)} = \frac{1000-600}{1000} = 40\% \qquad \text{Eq. 31}$$

The same method was used to obtain the 11 and 17 micron specific efficiencies. The reason for designating 7, 11, and 17 microns as the specific ratings instead of 7.5, 12, and 17.5 is that for AC Fine Test Dust the size distribution is such that there are more of the smaller particles in a sample, so an allowance was made for this distribution.

E. RESULTS AND CONCLUSIONS

In this section, representative curves are presented to show the separation efficiency test results. These results will be discussed in this section, and it will be explained, using these curves, how the final selection of the optimum hydroclone was made to satisfy the requirements for the prototype.

The series of tests were conducted in order to obtain the most efficient hydroclone diameter. From Fig. 44, it is easily seen that for a constant flow rate, the efficiency increases as the diameter of the hydroclone is decreased. However, this type of evaluation is good only as long as the pressure drop across the unit is not a factor to be considered in the selection. Since the pressure drop increased faster than the efficiency, it was necessary to run a second series of tests holding the pressure drop across the hydroclone constant. Fig. 44 shows that the 1.375 inch is the most efficient hydroclone diameter for pressure drop of 250 psi across the unit. Another test was conducted at 200 psi drop to assure that the tests were valid; and 1.375 inch again peaked out, but at a lower efficiency. From these tests, it was concluded that the 1.375 inch is the most efficient hydroclone diameter in the flow range specified by the contract.

The inlet diameter was investigated by using the optimum hydroclone diameter and a 250 psi drop across the unit, holding all other parameters constant and varying the inlet size. It had already been determined from a pressure drop study that single inlets were better than multiple inlets, so the investigation was confined to single inlets. From the curve in Fig. 46, the optimum inlet was obtained and has the value of 10/32 inch. Since the 10/32 inch and the 11/32 inch were so close, several tests were made on these two sizes with the result being that the 10/32 inch was better for each test.

The overflow diameter tests were conducted using the optimum hydroclone diameter and inlet while holding all other parameters constant and keeping a 250 psi pressure drop across the unit. Fig. 47 shows that the efficiency increases with increase in overflow size until 11/32 inch where a definite peak is evident.

Observations of other tests narrowed down the range of cone angles, and it was necessary to test only three to determine the optimum. It had been determined earlier that the best cone angle on the 1.50 inch hydroclone was 10°, so the cone angle tests were conducted in this range. All other parameters were held constant with the pressure drop

being fixed at 250 psi. Fig. 48 shows the peak in efficiency to also be at 10° for the 1.375 hydroclone.

The underflow diameter was investigated under the same conditions as the other tests, but using all of the optimum parameters from the previous tests. The best efficiency was obtained for an underflow diameter of 6/32 inch. The underflow graph is shown in Fig. 49.

SECTION VII

COLLECTION CHAMBER INVESTIGATIONS

A. INTRODUCTION

The hydroclone employs a closed type underflow as opposed to an open type. The open type underflow path occurs if the fluid is allowed to pass through the underflow port to a downstream line or to some other means of discharge, and not permitted to pass through the overflow nozzle of the hydroclone. A closed type underflow path is constituted when a hydroclone has a collection chamber integral with the hydroclone configuration.

The collection chamber employed on closed type underflows is the section of a hydroclone mounted below the apex of the conical cyclone separating section. As the name implies, this chamber collects the particles that have been separated by the hydroclone. The fluid and particles enter the collection chamber in a stream, termed the underflow stream.

At this point, it is advantageous to describe in general what happens to the particles and fluid while in the collection chamber, and after leaving the chamber. As the particles in a concentrated slurry of fluid and contaminant enter the collection chamber, the particles tend to move toward the wall of the chamber by virtue of their inertia. The heavier particles settle to the bottom of the chamber while some of the lighter ones remain in suspension and are affected by the fluid movement that exists within the chamber. Due to continuity of flow, the same amount of fluid must leave the collection chamber as enters the chamber. Fluid leaves the collection chamber through the center of the vortex that exist in the underflow port. The fluid then follows either of two paths. One path leads to the overflow port by means of the forced or inner vortex. The other fluid path leads to the free vortex of the cyclone section, and the fluid will again be reported to the collection chamber.

The objective of the hydroclone collection chamber study at OSU was to establish experimentally the optimum collection chamber parameters for a system. The tests conducted include:

(a) The effect of a subcone on chamber efficiency.
(b) The effect of baffles on settling.
(c) The effects of chamber geometry
(d) The effect of transient flow on the chamber efficiency.
(e) The contaminant concentration level at which the collection chamber needs to be cleaned.
(f) Visual observations to determine when to clean the chamber.
(g) Determination of optimum size of dirt holding capacity.

The object of these tests was to determine a general collection chamber configuration that results in a minimized value of contaminant

rejected to the overflow of the hydroclone.once the contaminant had entered the collection chamber. For example, if a collection chamber parameter was changed and the test showed more particles downstream than existed during a previous test under set initial conditions, then more particles were being rejected from the collection chamber. Comparative tests to determine the configuration that gave the minimized particle counts downstream of the hydroclone were conducted, and the procedure and results of these tests are shown on the following pages.

B. COLLECTION CHAMBER TEST

For the determination of the optimum collection chamber parameters, a study from an efficiency viewpoint was considered to give the best results. The general conditions for conducting this study was the same as that used for the previously mentioned separation efficiency study. Both studies used a HIAC inline sampling technique and continuous contaminant injection, all of which have been previously described in detail.

The optimum experimental hydroclone, as it was established from the pressure drop and separation efficiency studies, was used for all the collection chamber tests. Each collection chamber parameter was varied singularly, while holding all other parameters fixed, until a maximum separation efficiency was obtained using that particular parameter. The resulting collection chamber parameter was then used for the subsequent tests conducted.

Since the optimum experimental hydroclone was used for this test program, a flow rate of 15 gpm was used in order to get a more comprehensive contaminant size particle count. The 15 gpm flow rate was used for all parameters tested in this program except for final comparisons at 30 gpm.

C. PARAMETERS INVESTIGATED

1. Subcone Test

The effect of a subcone on hydroclone separation efficiency was investigated. The subcone is so called, since it is an inverted cone mounted to the apex of the conical separation section, concentric with the collection chamber. The opening in the apex of the subcone is coincidental with the underflow port of the separating cone, and the base diameter of the subcone depends on the subcone angle and the subcone length. The idea of the subcone was conceived from observations of the swirling fluid entering the collection chamber via the underflow port and creating turbulence. Contrary to the preferred activity, the turbulence in the chamber inhibits contaminant settling, thus giving particles an increased probability of being rejected to the hydroclone's overflow. The fluid motion and the entrained particles of the underflow stream are diffused by the subcone, whereby the turbulent velocities are decreased and a high separation efficiency is accomplished.

To optimize the subcone parameters, the cone angle and the cone's length were varied separately. The separating cones and the subcones were made of epoxy due to the simplicity of casting this material and economic aspects. The subcones were cast to the bottom of the separating cones, a facile operation which gave a "smooth" connection. First, the tests to determine the subcone angle while holding the length constant were conducted. The angles tested ranged from 10° to 16°, in 2° increments. The subcone length tests began with a 3-inch subcone which was decreased in increments of 1/4 inch for succeeding tests.

2. Baffle Test

After determining the optimum subcone, a baffle test was performed. The construction of the baffle consisted of 18 gage stainless steel strips, one-inch wide, assembled to fit a cylindrical collection chamber. The strips were arranged to form a square honeycomb with openings of 1/2 inch square. This configuration was selected since it would minimize the settling of contaminant on the top edges of the baffle. Efficiency tests were conducted with the baffle in two different locations in the collection chamber. The first position was with the baffle fastened to the bottom of the collection chamber. The second position was with the baffle suspended one inch from the bottom of the subcone.

3. Chamber Volume

Another parameter investigated was the collection chamber volume. This parameter was studied to determine if the volume affected the number of particles being rejected to the overflow. Three cylindrical-shaped collection chambers of different volumes were used. The largest volume to the smallest volume tested was .71 liters, .452 liters, and .232 liters. A cylindrical chamber with a single concentric opening in one end was used because it is adapted to simpler machining techniques and conforms to the existing flow pattern.

4. Transient Flow

One of the major parameters connected with the collection chamber is that of transient flow caused by pump pulsations and valve reactions. It was necessary to determine if these pulsations affected the hydroclone efficiency by stirring up the particles in the collection chamber. These tests were conducted in two phases. The first phase consisted of putting a 5.74 gm slurry of AC Fine Test Dust in the collection chamber and recording the effects on the HIAC particle counters for a three-minute period from start-up condition. The data collected during the first few seconds of this period showed particulate analysis during the transient state of starting the system. The remaining data were examined to determine if the counts increased in a steady ratio with time. This test was repeated for a 17.22 gm slurry to ascertain what effect a higher concentrate of contaminant in the collection chamber had on the range efficiency. Data were recorded at one-minute intervals.

During the next phase of this study, a 5.74 gm slurry was again added to the collection chamber. This time, the system was allowed to run at steady state conditions until all particles that were to be rejected from the chamber were rejected. Then, the flow control valve was closed and opened in a rapid motion for 10 cycles. The time from open to close to open consisted of about one second.

D. RESULTS AND CONCLUSIONS

The first test conducted was to determine an optimum subcone. The subcone angle was varied while holding the length constant; then, using the optimum angle determined from this test, the length was varied. These parameters were optimized by using the range efficiency method of analysis mentioned earlier. Data were recorded, and a curve was drawn of range efficiency versus subcone angle. This curve, plotted in Fig. 50, shows the optimum subcone angle to be 14° for the hydroclone tested.

The subcone length tests began with a 3-inch subcone, since this was the maximum length attainable with the present hydroclone body design and space limitations. Tests with subcones less than 3 inches in length showed that a subcone length less than 3 inches decreased the hydroclone efficiency. Therefore, the 3-inch length subcone was determined optimum. Fig. 51 shows a comparison of the optimum hydroclone with and without a subcone for 15 and 30 gpm.

Using the optimum hydroclone with the optimum subcone, tests were conducted to determine the effects of baffles in the collection chamber. From the data, it was concluded that the efficiency was not improved for either baffle position system. The reason for this lower efficiency may be accounted for from the fact that the flow pattern in the chamber produced by the subcone is disturbed by the presence of baffles. Also, changing the volume of the rotating fluid in the chamber may have some effect.

The collection chamber geometry was the next parameter investigated. This parameter was also tested by the range efficiency method. From test data, it is recognized that the larger chamber was more efficient. This is understandable since the larger chamber has a lower contaminant concentration ratio. The larger chamber also allows more settling time for the particles.

Test data were also collected for the effects of transient flow in the chamber efficiency. This data presents information for two types of transient conditions that occur in hydraulic system. The first condition -- that of system start-up -- was shown to have negligible effect on the chamber efficiency. From the start to the end of the three-minute testing periods, the system did not change efficiency rating. The transient condition only lasts for a few seconds, thus very few particles are picked up during this interval. A more concentrated slurry (24.25 gm/liter) was tested and no measurable difference was detected in the particle counts compared to the less concentrated slurry for the transient portion of the test.

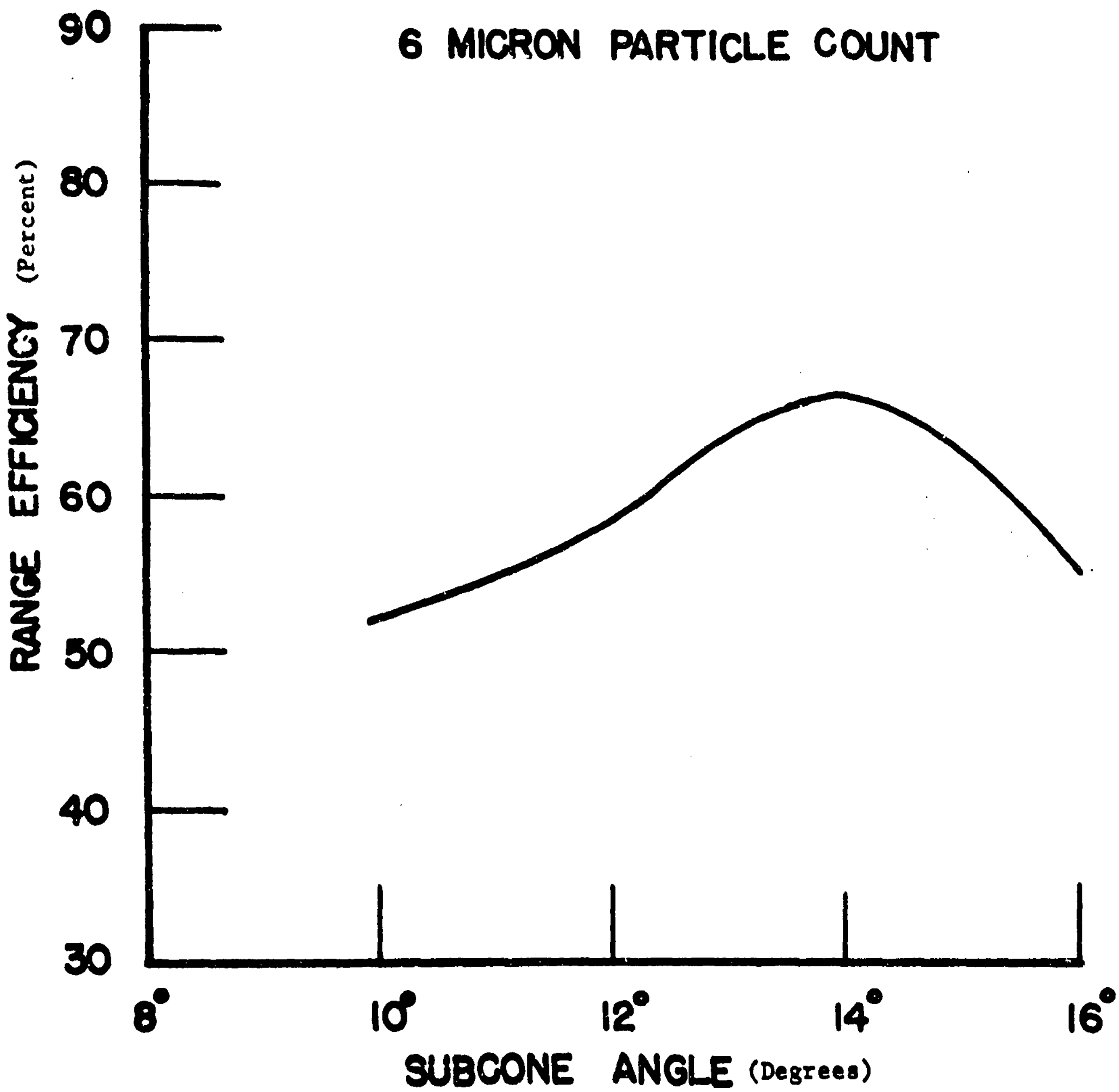

Fig. 50. Separation Efficiency Versus Subcone Angle with Flow Rate Maintained at 15 gpm.

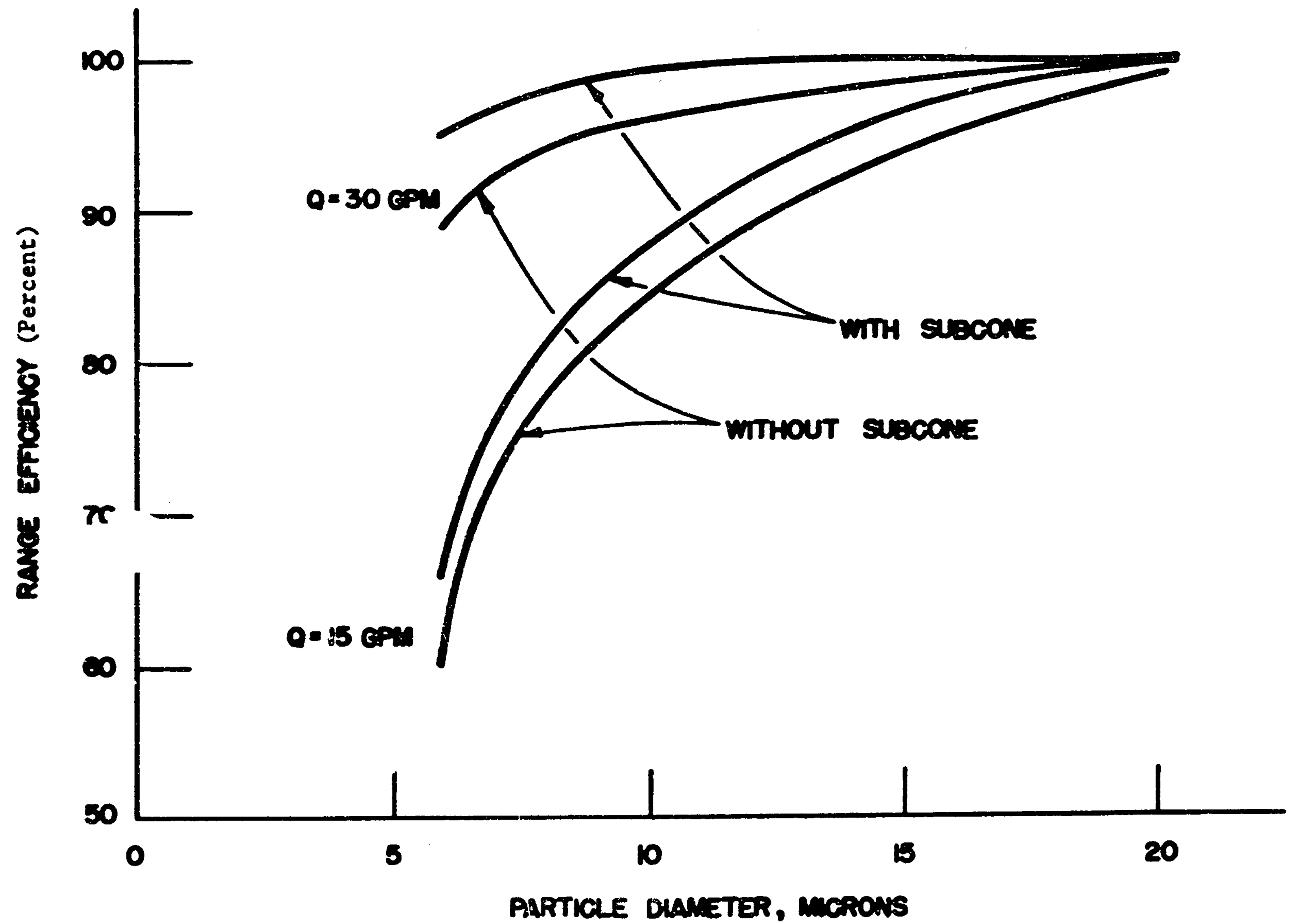

Fig. 51. Separation Efficiency for Optimum Hydroclone With and Without a Subcone for 15 gpm and 30 gpm.

The other type transient condition test simulated an actual hydraulic system being flushed. This test also proved to have little effect on particles being rejected from the chamber. Only six particles were recorded on the six micron counter after a one minute period. Therefore, on a probability basis, it can be seen that the transient conditions have no effect on particles being rejected from the collection chamber.

Tests on the contaminant concentration level at which the chamber needs to be cleaned, visual observation of the collection chamber during operation, and the dirt holding capacity of the chamber are all related to the collection chamber geometry tests. Therefore, these tests are dependent upon the particular volume selection for the collection chamber.

SECTION VIII

THE EFFECTS OF CHANGING FLUIDS ON HYDROCLONE PERFORMANCE

A. INTRODUCTION

The optimum hydroclone has been developed using MIL-F-5606. But the question arises as to whether a hydroclone optimized for one fluid can be employed in a similar system using a circulating media of appreciably different viscosity, and still achieve maximum performance of the hydroclone. Or does each system within a viscosity range require a unit of a specific set of dimensions in order for a hydroclone to be most effectual?

The $D_{50\%}$ equation (8) in Section V suggests that the execution of a unit will be altered when the unit is used with some other fluid, if the viscosity of this fluid differs appreciably from the design fluid. Therefore, it is the object of this section of the test program to study the effect on the operation of the hydroclone by changing the circulating fluid.

Since values have already been obtained for the dimensions of a hydroclone optimized for MIL-F-5606, this unit was utilized with PS 661 for testing; whereby the results could be applied to any two fluids of sufficient viscosity variation.

B. TEST PERFORMANCE

Using the hydroclone optimized for MIL-F-5606 hydraulic fluid, tests were conducted to determine the effect of viscosity changes on the performance of a given hydroclone. The two fluids used for these tests were MIL-F-5606 hydraulic fluid and PS 661 solvent. Separation efficiency tests were conducted on the aforementioned unit using the MIL-F-5606, and then repeated tests were performed using the PS 661 as the circulating media. The manner of conducting the separation efficiency tests was the same as described in Section VI.

The overflow diameter of the test hydroclone was then increased by 3/16 inch. This test unit was a duplicate of the optimum experimental hydroclone for MIL-F-5606, except for the change in overflow diameter. Using this altered unit, the efficiency tests were again conducted with the two fluid systems. These tests were conducted to establish whether congruity existed between the optimum hydroclone for any two fluids of distinct viscosity difference.

C. RESULTS AND CONCLUSIONS

Tests conducted on the two fluids, MIL-F-5606 and PS 661, which have significantly different molecular viscosities, show that a

hydroclone will achieve a better separation efficiency with the lower viscosity fluid than with the higher one provided the optimum hydroclone for each test fluid is used. This is to be expected from examination of the $D_{50\%}$ equation in Section V. The tests also suggest that the optimum hydroclone for the higher viscosity fluid MIL-F-5606 is not optimum for the low viscosity fluid. Changing a single dimension on a hydroclone that is optimized for the MIL-F-5606 reduces the separation efficiency with MIL-F-5606. Likewise, a decrease in the separation efficiency with PS 661 should be expected when a less viscous fluid is used with the hydroclone optimized for MIL-F-5606.

The optimum unit for MIL-F-5606 described in Section VI was tested with PS 661 solvent as the circulating media, and the $D_{50\%}$ size was calculated by the same technique used in optimizing the hydroclone in Section VI. One paramter, the overflow diameter, was then increased; and the same test procedure was repeated. The results of these two tests are shown in Fig. 52. After changing the overflow diameter, the hydroclone performance was improved, demonstrating that the optimum unit for MIL-F-5606 is not optimum when used with PS 661.

The lower $D_{50\%}$ observed using PS 661 as the circulating fluid can be explained by noting the lower viscosity of this solvent, (1.92×10^{-6} lb-sec/in^2 at 106°F compared to 1.42×10^{-6} lb-sec/in^2 at 120°F for MIL-F-5606). This decrease in $D_{50\%}$ can be predicted from the $D_{50\%}$ equation. The significant factor, however, is that the optimum hydroclone configuration for one fluid is not necessarily optimum for another.

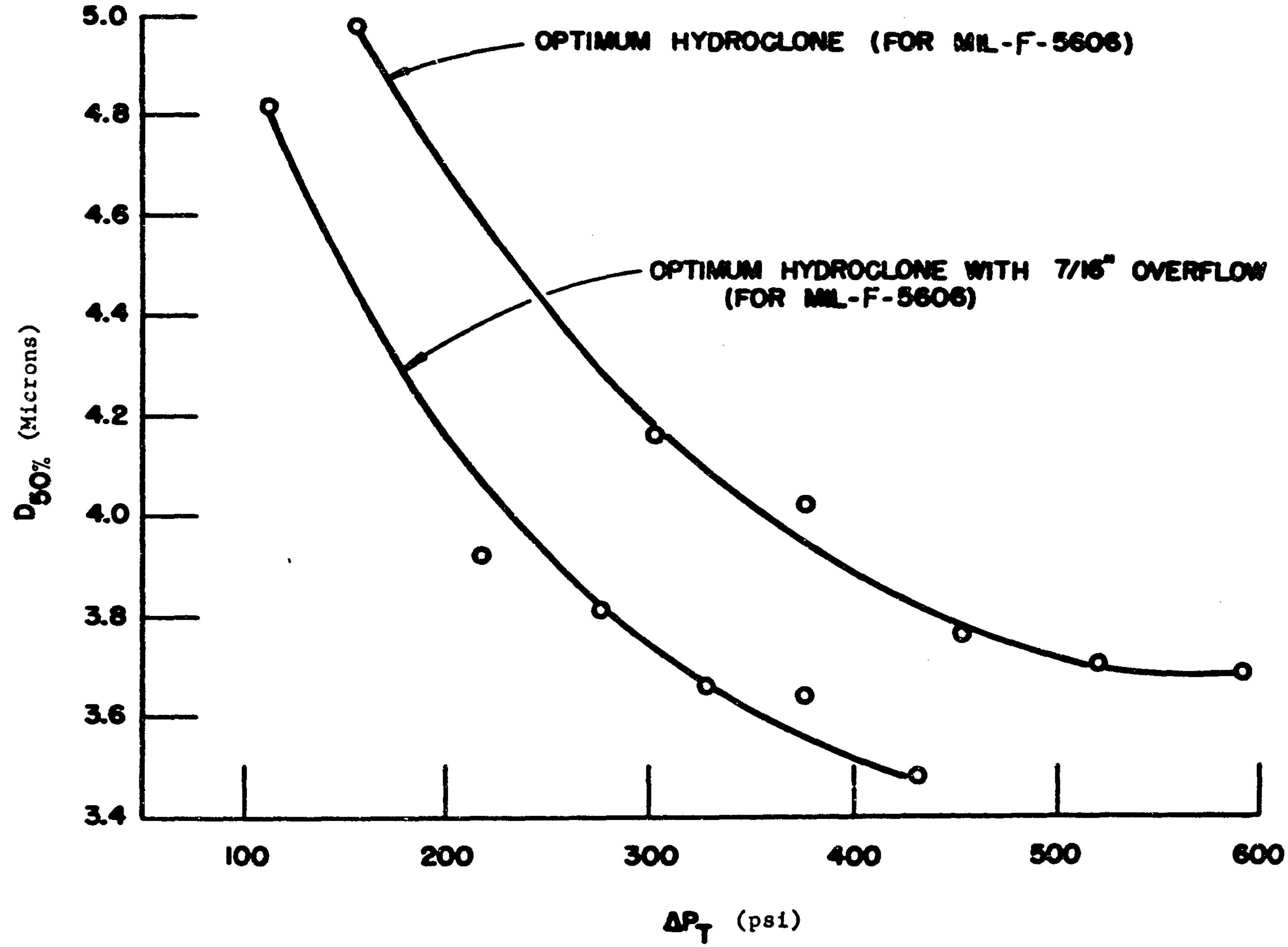

Fig. 52. $D_{50\%}$ Versus ΔP_T for Hydroclones Using PS 661.

SECTION IX

ENDURANCE TESTING

A. INTRODUCTION

The previous sections have disclosed what can be expected during the performance of a hydroclone. However, regardless of a hydroclone's achievement during relatively short intervals of operation in the laboratory, unless a material could be found for its fabrication that would remain undamaged during continuous operation, the hydroclone would be inapplicable to any practical use. Therefore, of prime importance during this study was the intensive investigation to find those materials whose properties apparently conformed to the demands of the activiated system.

In order for a material of a hydroclone to "provide reliable and efficient service," it must be able to withstand the temperatures, pressures, and abrasion encountered during a hydroclone's operation. Since most of the wear in a hydroclone exists in its cone section, it is for this component that the material selection is focused. Although the majority of materials used as cone liners will withstand the pressures and temperatures (200°F) of most hydraulic systems, few of them are able to resist the abrasive action. Therefore, abrasion is considered the main problem.

The erosion of hydroclone materials is caused by the contaminant particles as they come in contact with the internal surfaces of the unit. Although much of the internal surface of the hydroclone is sufficiently protected from wear by a fluid boundary layer, there is a highly critical area near the apex of the conical section that is subjected to extremely abrasive action by the particles. Fig. 53-b shows a polyester (epoxy) resin cone that has been damaged by erosion during the normal operation of a hydroclone.

As has been discussed in Section II, contamimant particles suspended in the fluid enter the cyclone section with vertical and tangential velocity components. Once in the cyclone section, the particles experience a radial force due to the drag of the fluid as the fluid takes on a radially inward velocity component in the free vortex field. A particle entering the free vortex field will either travel on to the boundary layer along the surface of the conical section, travel in an inward and downward spiraling path to some equilbrium radius, or spiral into the forced vortex region near the center of the cone. The path a particle takes is dependent upon the particle's mass, its projected area, and its tangential velocity.

Particles that enter the boundary layer of the cone section travel downward in a relatively slow moving spiral path toward the hydroclone's underflow. Where a dense boundary layer exists in the cone section, wear of the surface is practically non-existent.

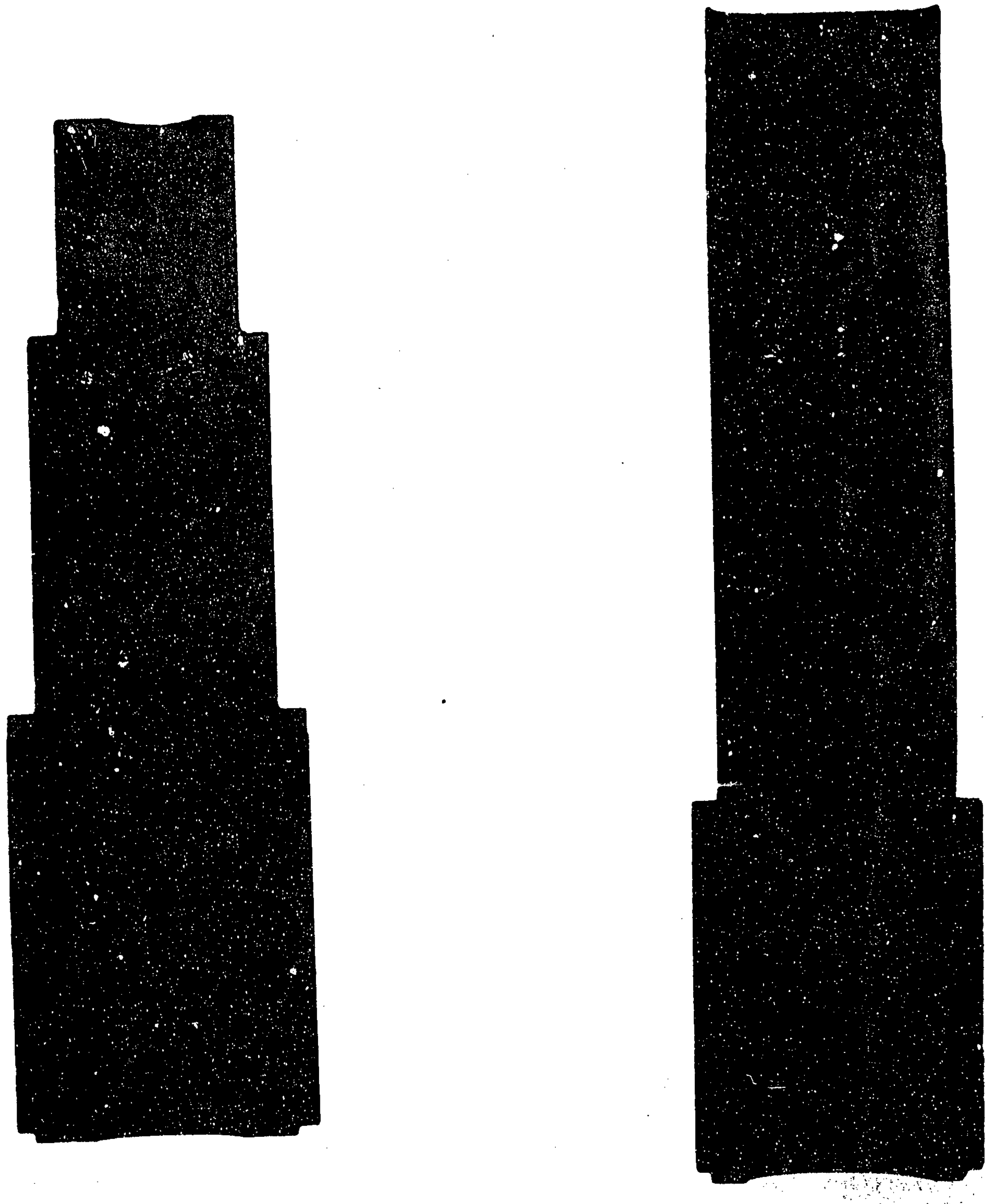

Fig. 5[illegible]. Cross Section of Polyester Resin Cone Showing Damage by Erosion During (a) Endurance Testing; (b) Normal Test Operating Conditions.

Particles that reach an equilibrium radius in the free vortex field contribute to the erosion near the cone's apex. This can be explained by calling attention to Fig. 7 in Section II which shows curves illustrating particle equilibrium contours in the conical section. In the upper part of the cone section, the curves are seen to be approximately parallel to the cone's surface; and particles which have reached their equilibrium radius in that region will orbit in the free vortex field as they spiral downward. In the lower regions of the cone section, near the apex of the cone, the equilibrium contours converge; and some of the contours intersect the cone's surface. The result is a high concentration of orbiting particles in the lower region of the cone. Furthermore, particles that are forced against the surface of the cone receive an upward reactive force component from the cone's surface, resulting in a doughnut-shaped ring of orbiting particles. The ring simulates a small grinding wheel acting on the surface of the cone; it wipes out any boundary layer protecting the cone and picks up any particles that are contained in the boundary layer. Finally, as the particle concentration saturates, particles are rejected downward to continue their journey through the underflow nozzle to the collection chamber. Materials for constructing a cone are required to be highly resistant to abrasion in order to withstand the conditions that exist in the described critical region.

B. MATERIALS

Some of the materials were considered for the hydroclone construction because of their satisfactory endurance in other applications. Others were selected for testing because available literature indicated these materials possessed properties essential to withstand the high standards required of a hydroclone.

Foremost in the consideration of the properties of materials for the cone construction were abrasion resistance, hardness, maximum working temperature, tensile compressive strength, resistance to various types of fluids, production costs, and ability to be cast or machined. After much deliberation, several seemingly appropriate materials were selected for testing. These materials were Polyester resin, Anodized 6061-T651 Aluminum, Urethane rubber, Aluminum 2024-T4, and ceramic. Some of the important properties of the materials, as related to the hydroclone,are discussed in the following paragraphs.

The polyester resin is a commercial grade of resin manufactured by the Fiberglass Evercoat Company. The physical properties of this resin include a tensile strength of 55,000 psi, compressive strength of 60,000 psi, flexural strength of 70,000 psi, and heat resistance to a continuous temperature of 250°F. It is chemically resistant to most substances, the exception being medium to strong acids and alkalies. This material also possesses the characteristics necessary for its easy casting and machining. To cast the cones, a conical mold was coated with a layer of the polyester resin. The resulting cone was one containing a hard, smooth, surface. Although the polyester resin is ideal for attaining a cone with a smooth surface, because of the pressures encountered during the performance of the hydroclone, it was necessary to add strength-

supporting aluminum powder to the resin when constructing the remainder of the cone. In addition to adding strength to the material, the aluminum powder decreased the brittleness of the composite material, permitting better machining.

The aluminum tested was 2024-T4, an aluminum-copper alloy. This material has a tensile strength of 68,000 psi, a yield strength of 47,000 psi, and a shearing strength of 38,000 psi. Its easily machined surface can be polished to a very smooth finish. Cones were constructed from this material for previous hydroclone studies at Oklahoma State University. These cones were used as test devices, and the material gave a satisfactory performance.

Anodized aluminum was also tested as a possible material for the hydroclone. A blind cone was machined from 6061-T651 aluminum, since this mode of formation was recommended by the anodizing firm. This material is an aluminum, magnesium, and silicon alloy with a tensile strength of 45,000 psi and a yield strength of 8,000 psi. The Stanford process was used in anodizing the material. This process involves an electro-chemical action, using sulfuric acid as the electrolite, which builds up a surface hardness of 55 Rockwell C scale, approximately .002 inches thick on open cones. The process leaves the surface black in color. The hardness of the blind cone used for testing was about 20 to 25 per cent less than that of an open cone (as estimated by the anodizing firm) because the electrolite could not flow through the blind cone.

Another material considered for the cone material was Urethane rubber manufactured by E. I. Du Pont de Nemours and Co. At room temperature, the raw Urethane rubber is in liquid form, making possible its easy casting into any form desired. Yet, in its cured form, this rubber has a machinability which approaches that of some metals. Machining of this rubber can be accomplished on standard metal working equipment; therefore no specialized equipment is required for fabricating a hydroclone from it. Although in uncured form, it is a liquid; at room temperature, the cured polymers can be made as hard as 78 Shore D at this same temperature. The material retains its physical properties while subjected to continuous operation below 212°F, which is above the operating temperature of many hydraulic systems. The chemical resistance of Urethane rubber is still being investigated by the manufacturer; however, oil and grease have been found to have little effect on properly compounded Urethane. Aromatic and polar solvents will cause moderate to considerable swelling. An outstanding feature of this material is the capability of withstanding abrasion.

The ceramic selected for cone tests was Coors Porcelain Company's AD-85 which is composed of aluminum oxide crystals bonded together with silicates. The alumina ceramics are formed by alpha alumina crystals held together by their interlocking structures and by an amorphous, silicecus matrix. As the alumina content increases, the amount of matrix material decreases, therefore increasing the abrasion resistance. This material can be subjected to high temperatures and pressures without danger of failure in the material. It is resistant to corrosive

attack, except in the presence of strong alkalies or hydrofluoric acid. The material has a hardness of 75 Rockwell 45 N, a maximum working temperature of 2550°F, and a modulus of elasticity of 31.9×10^6 psi. Its abrasion resistance is excellent, except where the abrasive agent is in the hardness range of diamonds, or where pressures exceed the compressive strength (over 240,000 psi) of the material. The material can be finished to a very smooth surface.

C. ENDURANCE TEST PROCEDURE

To test the materials, a hydroclone housing was constructed from aluminum as shown in Fig. 54. The liners were built with the underflow closed, and the underflow chamber was connected to a pressure tap at the top of the cone to equalize the pressure in the underflow chamber and the pressure at the top of the cone. This provision for equalization of pressure at the top of the cone and the underflow was included to keep the bottom of the cone from blowing off should a large pressure be encountered.

At the initiation of each test, a slurry of contaminant and hydraulic oil was inserted in the test system. Because the liners were made with the underflow plugged, most of the contaminant that was collected in the cone stayed in the cone, becoming more concentrated as the test progressed. Consequently, injection of additional contaminant in the system was not necessary to subject the hydroclone to rigorous testing. By using this method, the test time was decreased because the large concentration of particles caused the cone to wear quicker than it would under normal use. The particles of the cone material which were worn from the surface of the cone helped replenish the contaminant in the cone; and because these particles are as hard as the cone surface, this also decreased the testing time required. An optimum size cone was designed and constructed of each of the materials. The dimensions of the cone are shown in Fig. 55.

These tests were performed for the purpose of comparing the endurance of each material with that of the other materials, and were not intended as an indication of the life of the materials during hydroclone operation. In other words, the materials would remain undamaged longer under normal operation than under the test conditions because, with an open underflow, the contaminant concentration does not become nearly as great as in the test cones.

Since the purpose of the test was the comparison of the erosion endurance of the materials, the testing conditions (temperature, pressure drop, flow rate, amount of contaminant injected, checking time, and cone parameters) were kept as congruent as possible for each test. The dimensions of the cones used for the test are shown in Fig. 54.

The test procedure for each cone was conducted in the following manner. The liner was installed and filled with a slurry of MIL-F-5606 hydraulic oil and 5.7 grams of AC Coarse Test Dust. The test system was slowly brought up to the operating pressure drop across the

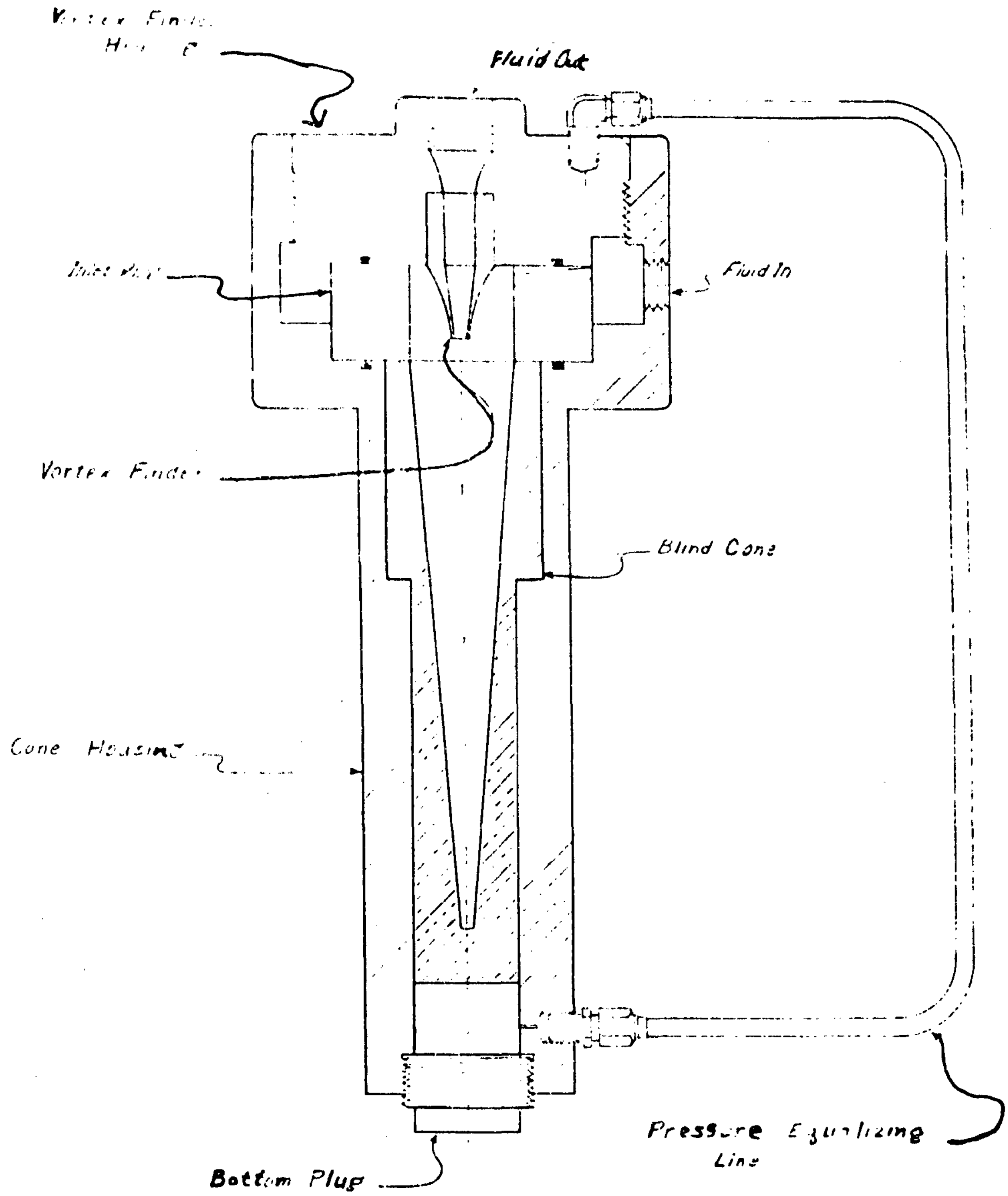

Fig. 54 Schematic of the Hydroclone Used for Endurance Testing.

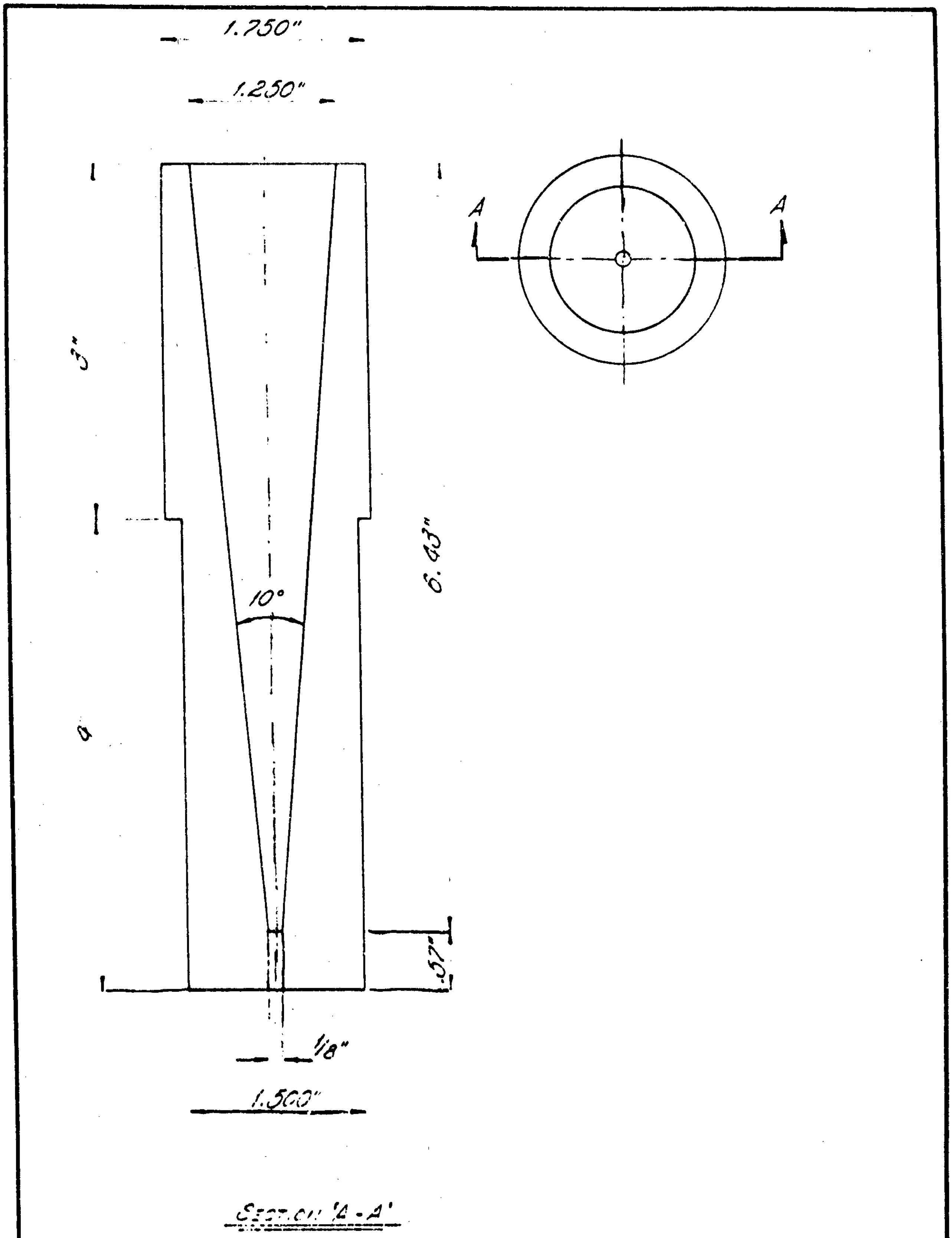

Fig. 55. Closed Hydroclone Liner Used for Endurance Testing.

hydroclone of 500 psi and a system flow rate of 25.5 gpm. This condition prevented the contaminant in the cone from being washed out of the cone. A temperature of 120°F was maintained in the system. At one-half hour intervals, the liner was removed and visually inspected for wear. If the cone showed signs of erosion, it was considered to have failed and the test was complete. When no indication of wear was observed, the hydroclone was reassembled and the cone tested for another half hour. Testing was continued on each liner until the cone failed or showed no evidence of wear after extended test periods.

D. RESULTS AND CONCLUSIONS

In the selection of a material for hydroclone fabrication, due consideration should be given to all the factors which make a material feasible for this application. Several materials were found which seemed to have the appropriate properties; however, their resistance to the abrasion encountered in a hydroclone was questionable. The endurance test then was designed to permit a comparison of materials from qualifying evidence before selecting a material for hydroclone construction.

Fig. 53 shows the cross sections of two polyester resin hydroclones which have been exposed to contaminant abrasion. The picture at the right demonstrates the wear in a cone that was utilized during normal test conditions. The picture on the left exhibits a cone with a closed underflow that was used for endurance testing. The two grooves apparent in the cone with the closed underflow are due to two flow rates being employed in the test interval. The similarity between the wear of these two cones justifies the use of the rigorous endurance testing for obtaining expeditious results for the abrasive wear in an operational hydroclone.

The polyester resin cone was tested first, followed by the tests on the 2024-T4 aluminum cone and the anodized 6061-T651 aluminum cone. The life of these three cones were relatively short when subjected to the rigorous endurance tests for within one hour and forty minutes of testing grooves had worn in each of these materials.

At this time, a total of ten hours of testing has been conducted on both the Urethane and the ceramic cone; and neither of them show any signs of wear. Although no evidence has been found to disqualify either of these materials for hydroclone fabrication, the Urethane rubber was selected for the prototype hydroclone construction because of economic aspects and the availability of Urethane hydroclones prior to the contract termination.

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

The design, development, and application of miniature hydroclones prototypes for de-contaminating hydraulic fluid in Ground Support Equipment have been successfully established under the referenced contract. The general requirements for the implementation of the Hydroclone Project necessitated the acquisition and construction of specialized equipment. With this equipment, a veritable hydraulic system was simulated; and precision measurements of the system variables were recorded which made possible the hydroclone performance study. Using MIL-F-5606 hydraulic fluid as the dispersion medium and AC Fine Test Dust as the contaminant, comprehensive testing has been conducted to obtain the optimum parameters for a hydroclone that will produce the maximum separation efficiency with the minimum pressure drop across the hydroclone. Thus, the parameter studies included an intensive investigation to determine the effects of varying the parameters of a hydroclone on both the pressure drop of a hydroclone and its separation efficiency. And from the investigation, it has been shown that all hydroclone parameters must be optimized for a specific set of operating conditions. Hence, the optimum hydroclone design for a particular fluid under specified conditions will not be optimum for another fluid or different operating conditions.

The equations that are presented in this report can be used effectively in the design procedure to determine approximate hydroclone parameter values. Separation efficiency tests are then conducted for final optimization of the parameters.

The correlation of the pressure drop studies and the separation efficiency studies can best be described by their application to the design of a hydroclone. It has been found that the $D_{50\%}$ equation (8) can be used to approximate the optimum hydroclone diameter for a specific fluid. And, using this diameter as a design guide, an experimental hydroclone is then used for separation efficiency tests conducted for the precise determination of optimum hydroclone parameters.

In order to design an optimum hydroclone, the following procedure is presented:

(a) Select the flow rate Q and the $D_{50\%}$ desired to meet the design requirements.
(b) Select V_o = 1.5 (a conversative value).
(c) Using the $d_{50\%}$ equation (See Equation 8A) solve for the radius of the hydroclone, r_c, using the values of absolute viscosity, and density of the liquid, ρ_L, and dimensionless overflow radius, δ, cone angle, φ, and effective dimensionless inlet radius, β_e, obtained for the optimum 1.375-inch hydroclone for MIL-F-5606 at the same flow rate, Q. (The cone angle, φ, of 10^o along with the 14^o subcone angle will be the optimum cone and subcone angles regardless of the fluid used.)

(d) After a value of r_c has been obtained, an approximation of the optimum hydroclone diameter for the desired fluid and operating conditions has been obtained.

(e) Using the calculated value of r_c, an experimental hydroclone should be fabricated and efficiency tests conducted to determine the optimum parameters for the fluid specified.

A hydroclone of 1.375 inch diameter has been found to be optimum for MIL-F-5606. For the design of a hydroclone that will produce the best separation efficiency with the least pressure drop, and will be used with any hydraulic fluid within the viscosity range of MIL-F-5606 and MIL-F-7808, the same hydroclone of 1.375 inch diameter designed and tested by OSU personnel will be optimum. However, with fluids more or less viscous than these fluids, a change in the tangential velocity and characteristics of the fluid must be accounted for; and a different optimum hydroclone will prevail. Examples of such fluids are cleaning solvent (PS 661), jet fuel, and water.

Fully operational, prototype hydroclones for MIL-F-5606 hydraulic oil have been designed and experimentally tested. The parameters which wer. optimized, and their final values, which comprise the prototype configuration include:

Hydroclone diameter - 1.375 inches
Diameter of inlet - 10/32 inch
Overflow diameter - 11/32 inch
Single inlet
Cone angle - 10 degrees
Underflow diameter - 6/32 inch
Subcone angle - 14 degrees
Subcone length - 3 inches

Using these parameters, a field-serviceable, prototype hydroclone was fabricated, and separation efficiency tests were conducted. The results of these tests (shown in Table 1) indicate that the prototype hydroclone has exceeded all expectations in performance and can be described as a very efficient unit when properly applied. Laboratory tests verified that the prototype hydroclone exceeded the requirements for a five micron separation unit using both contaminants cited (Carbonal Iron E and AC Fine Test Dust) in MIL-F-27656A for low micron filter performance tests.

Another important investigation contributing to the hydroclone application was the endurance test program for the selection of a material from which to fabricate the prototype hydroclone. Since the use of a hydroclone with a closed underflow was found to expedite the endurance testing and still produce representative results, this configuration for the hydroclone was used for these tests. Several materials were found which seemed to possess the appropriate properties for hydroclone fabrication; however, no information on their resistance to abrasion, as exists in the hydroclone, could be found. Therefore, the endurance tests were performed prior to a material selection. Of the materials tested, which included Polyester Resin, 2024T4 Aluminum, Anodized 6061-T651 Aluminum, Urethane Rubber, and Aluminum Oxide Ceramic, the Urethane Rubber and Ceramic were found to have a high degree of

resistance to abrasion. No evidence has been found to disqualify either the Urethane Rubber or Ceramic for hydroclone construction; however, the Urethane Rubber was selected for the prototype hydroclone fabrication because of economic aspects and its availability at this time.

Since the prototype hydroclones satisfy all the necessary requirements for ground support equipment, as presently known, an intensive field test is warranted. This field test should include the determination of the suitability and capability of the unit on hydraulic carts at Air Force Bases. Such tests would establish the endurance limits and reliability of critical hydroclone parts and would determine their compatibility with a specific hydraulic system.

A study should be conducted to compare the hydroclone performance with conventional-type filter units. Using service-type contaminants, such a study should also incorporate the establishment of particle-size distribution characteristic curves for the hydroclone and conventional filter.

Finally, a test procedure should be established for verifying hydroclone performance which would be the basis for specifications (military) for cyclone separators.

APPENDIX I

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	Valve	Model 1406 1/2" Motor Operated Control Valve
C_1 C_2	Particle Counter (2)	High Accuracy Products Corp. Model PC202 Electronic Particle Counter
FM_1 FM_2	Flow Meter (2)	Fischer and Porter Co. Rotameter Model No. 11-3000 Range 0-20 GPM
R_2	Injection Reservoir	Cylindrical Shape 5 Gallon Capacity Locally Fabricated. Equipped with motor-driven agitator.
P_2	Injection Pump	Cessna Aircraft Co. Model H20202 Gear Pump Cap. 1.5 GPM at 2000 PSI
D_1	Variable Speed Drive	Allis Chalmers Mfg. Co. Frame 215 AG3 Variable Drive Unit, Horizontal Ratio 6:1, 1720 RPM
M_3	Injection Pump Motor	Allis Chalmers Mfg. Co. Type GF Induction Motor 3 Phase 3 HP 1150 RPM
V_9 V_{10}	Diversion Valve (2)	Double A Products Co.

B. PRESSURE TEST SECTION

P_3	Circulating Pump	Cessna Aircraft Co. Model P200020 Gear Pump Cap. 33 GPM at 1750 RPM and 2000 PSI
	Sump Pump	Oberdorfer Co. Model 500 lb Cap. 26 GPM at 1750 RPM and atmospheric pressure
M_4	Circulating Pump Motor	Allis Chalmers Mfg. Co. Type G 50 HP 1725 RPM Double Shift with 1 ea size 0 Cutler-Hammer No. 9582H6485T Magnetic Starter
M_5	Flow Motor	Cessna Aircraft Co. Model M21012-2C Flow Motor 2160 RPM at 30 GPM
F_3	Magnetic Pickup	Electro Products Laboratories, Inc. Model M3010-A Magnetic Pickup
F_4	Amplifier	Lafayette Radio Co. Model LA-55, Audio Amplifier
N_2	Electronic Counter	Beckman Instruments Co. Model 5210P E Put Motor
H_2	Heat Exchanger	Young Radiator Co. Model HF-303-HY-1P Tube and Shell Heat Exchanger
V_{12}	Flow Control Valve	Waterman Hydraulics Corp. Model DH 1417K Adjustable Flow Regulator
V_{11}	Pressure Relief Valve	Double A Products Co. Model BT4-180-2

	Temperature Indicator	Marsh Instrument Co. Model B Range 30-220°F
	Pressure Gage (2)	ACCO Co. Helicoid Gage Model GW2000-10
V_{13}	Flow Division Valve	Double A Products Co. Model KJ-2-180-0 Solenoid Operated 4-Way Valve
A_1	Magnetic Clutch	Warner Electric Co., Stationary Field Clutch Coupling with spline drive armature, inside mounted, 1 1/2" bore
	Clutch Control-Rectifier	Warner Electric Co., Model 5400-27 115/230/460/575 Volts AC, 90 Volts DC
J_1	Digital Voltmeter	Cubic Corp. Model V-46AP, Range 0 to 100 Volts DC
G_3	Pressure Gage	Heise Co. Model H35577 Precision Pressure Gage, Range 0-2000 PSI
E_1	Differential Pressure Transducer	Pace Engineering Co. Model P210, Range 0-100 PSID
E_2	Differential Pressure Transducer	Pace Engineering Co., Model P3D (0-2000 psid)
R_3	Reservoir	Locally Fabricated, 14 gage Steel, Inverted Cone Shape, 120 gal. cap.
U_1	Transducer Demodulator	Pace Engineering Co., Model CD10 Multi-Fluid Test Stand

C. NON-LUBRICATING TEST STAND SECTION

P_4	Circulating Pump	Cessna Aircraft Co. Model P20020 Gear Pump, Cap. 33 GPM at 1750 RPM and 2000 PSI
A_2	Magnetic Clutch	Warner Electric Co., Stationary Field Clutch Coupling with Spline Drive Armature inside Mounted with 1 1/2" Bore.
V_8	Pressure Relief Valve	Texstream Corp. Type 605 2000 PSI Relief Valve
R_4	Reservoir	77 Gallons cap. SS construction
FM_3	Flow Meter	Locally Fabricated, venturi tube section with aneroid monometer.
H_3	Heat Exchanger	Young Radiator Co. Model 67219 Shell and Tube Heat Exchanger